A Study of Human Gaits across Different Speeds

Rawesak Tanawongsuwan and Aaron Bobick
College of Computing, GVU Center,
Georgia Institute of Technology
Atlanta, GA 30332-0280 USA
{tee|afb}@cc.gatech.edu

Abstract

This paper explores time-distance gait parameters across walking speeds. Our approach consists of designing an experimental setup to gather walking data at various speeds, analyzing time-distance features with respect to speeds. We explain the motivations of this study and the details of the experimental setup that allows people to walk naturally on the ground level floor and at the same time achieve the walking speed-control goal. The characteristics of gait features are demonstrated at the inter- and intra-individual variations.

1 Introduction

Gait recognition research currently has focused on analyzing video sequences of human walks directly. Many features have been proposed to capture individual gait characteristics. Most approaches put a lot of efforts to get the segmentation and tracking algorithms to work reasonably well in various existing walking databases.

Normal walking conditions (constant and natural walking speed, no object to carry, level ground walking, etc.) are ones of the main assumptions made in most current techniques. Many proposed features and techniques will not work well if these conditions do not hold. Even though most of the time gait patterns are repeatable, changes in walking conditions can have effects on the patterns themselves. There are many factors from our daily walking activity, such as, locomotor speed, stride frequency, walking surfaces, load carrying , etc. that can influence the inter- and intra-individual variations. The understanding of the characteristics of gait patterns under various gait conditions will help improve and scale the techniques in the gait research.

We are interested in human gaits across different speeds. In particular, we want to understand the patterns of time-distance gait parameters such as stride length, stride time, and cadence which are potentially measurable by computer vision techniques, under various speed conditions. In this paper, we present a detail study of human gaits under different speeds in which an experimental setup to gather gait data at various speeds is explained and the characteristics of these features with respect to speed factor are investigated.

2 Related and previous work

Humans can walk up to 4 m/s [11], but the speed of roughly 2.2 m/s is the natural transition point from walking to running [11, 12]. Several works in the past have shown that increasing velocity is normally achieved by increasing both cadence and stride length. [14, 13] study the influence of walking speed on gait parameters to find out the *normal* ranges for those parameters. The results can be used as a reference for comparison with other pathological cases.

From a human identification perspective, human gaits are observed in various situations, for examples, side-, frontal-, or arbitrary-views, and indoor versus outdoor scenes [1, 2]. Many features are proposed in the literature for gait recognition tasks including optical flow, joint angles, silhouette, etc. Example works include appearance based approaches where the actual appearance of the motion is characterized [3, 4, 5]. Several works extract parameters of body and gait, such as, stride length, cadence, height, joint angles to use in the classification tasks [1, 6, 7, 8]. In [9], they analyze the identity information contained in the lower-body joint-angle trajectories using the data measured with 3D motion capture system. [10] has shown the visual discrimination of children from adult using stride-based properties of their walking style.

3 Experimental Setup

To study gaits across various speeds, we need to gather walking data at different speeds. Walking speed, in many studies, is not varied systematically as an experimental control factor. Subjects usually are asked to walk in their preferred walking speeds on a walking path. Since it is difficult to control or guide the subjects to walk naturally on the floor at the similar speeds, a treadmill system is commonly used in many studies to control the speeds of human.

Many studies in the human movement study and biomechanics use a treadmill to study many characteristics of human locomotion, for examples, [15, 16, 12, 17, 18]. In [12], a treadmill is used to control walking and running subjects for comparison purposes. The symmetry of gait is studied using a treadmill-based system in [15].

The advantages of using a treadmill for gait analysis are that researchers can precisely control the motor speed and the area needed to perform the experiment is rather small. A treadmill-based system allows for a convenient application of monitoring equipment and provides a controlled setting by which multiple gait cycles can be analyzed. However, walking on a treadmill seems unnatural. In fact the differences between walking on the normal level floor and the treadmills have been reported. [19] reports that there are small differences between walking on a treadmill and on the ground but report no effect on the symmetry. [20] finds significant differences in sagittal knee joint motion between treadmill and overground walking when subjects are given 1-2 minutes to familiarize themselves on the treadmill. [16] also reports that subjects should be given at least 6 minutes to familiarize themselves with treadmill walking in order to obtain knee kinematics and temporal-distance gait measurements that can be generalized to those of overground walking. Another drawback of the treadmill system is that many patients with disabilities can not walk on it safely especially in the cases

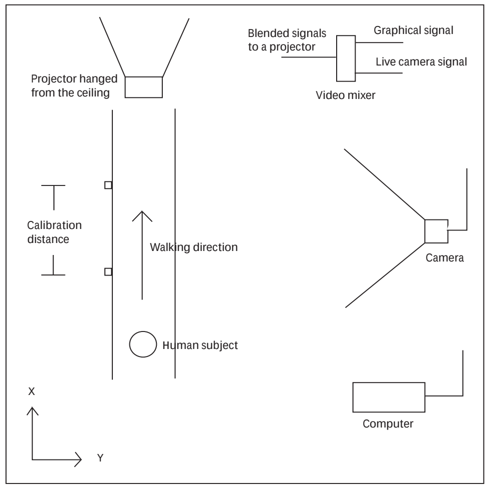

Figure 1: A video camera is placed in a side view of the walking direction. A computer generates graphical moving lines with a certain speed (V m/s). A video mixer device mixes both signals and send to the projector, which projects them onto the wall in front of the subject.

of pathological studies.

To quantitatively assess the effects of speed variation on the gait parameters during walking movements, we design a set of experiments in which people can walk naturally on the ground level floor and at the same time achieve and remain at certain speeds. A key idea is to have an indicator showing the subjects' current position as a feedback to them so that they can make any necessary adjustment to their walks to reach the desired speed.

One possible setup is to have some arrays of lights (such as those in movie theaters) lined up on the floor. There will be a device that controls the states of lights (on and off) to simulate a certain movement speed. All subjects have to do is to walk along the moving lights in a coherent way. This idea is essentially similar to creating a *physical friend* to whom subjects have to walk along at the same pace. One drawback of this setup is that a person has to look down or glance on the floor or to the side to see the physical friend.

Another possible idea is to use an audio cue (metronome device) to give the subjects the mark of exact time generated by regularly repeated ticks. This way, we can only control step frequency but not speed which also depends on step length. If we want subjects to walk at a higher speed, the metronome will be set to tick at a greater frequency. This idea is good in terms of helping to free the burden of human perception and letting sound to indicate the walking speed. The ticks can be used to control events, for example, foot fall rhythms. However, it is difficult to calibrate the frequency of ticks corresponding to a desired speed.

The the setup used in this speed-control experiment, takes the advantage of natural human perception. Perception is one of many channels which people receive feedbacks

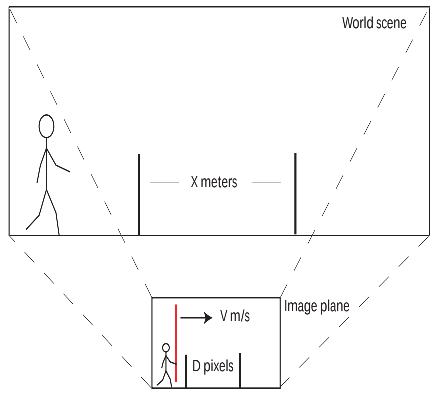

Figure 2: A typical real-world scene from the side-view video camera.

Figure 3: An example image projected onto the wall.

from the environment. Therefore, we allow people to see their real-time walking images in front of them. We also overlay *a virtual friend* or some graphical representation (i.e., a vertical line) which moves along them in the image frames at a certain speed. All the subjects have to do is to make sure that they move at the same pace as their virtual friends on the projected images. If they notice that they start to fall behind, then they have to walk faster. Since the graphical lines move at a certain constant speed, people do not have to concentrate on looking at the images in front of them all the time once they can retain the desired speed.

The speed of the graphical moving lines needs to be calibrated properly. We simply assume that the camera lens are not too wide and that each pixel covers the real-world space roughly the same distance. The lines need to be redrawn and updated at the speed of DV/X pixels/s, where X is the distance in meters in the scene, D is the number of pixels that covers that distance, and V is the speed (m/s) that we want to simulate. Figures 1 - 3 show the overview of our speed-control setup and an example image seen by walking subjects.

The hardware components that we need in this speed-control setup are a video camera, a computer, a video mixer, and a video projector.

- The video camera is placed parallel to the walking path showing the subject side-view. The camera signals show the subject's live walking action which is sent to the video mixer.
- The computer has a simple graphical program (more details in the next section) that draws vertical lines moving across at a specified speed. The output signal is sent to the video mixer.
- The video mixer blends signals from the camera and the computer together and sends to the video projector.
- The projector then projects the blended signals onto the wall in front of the subjects.

Subjects can be guided to walk at different speeds, ranging from slow to fast. Because we are interested in natural, unconstrained locomotion, only general, qualitative instructions are provided and each subject is free to choose his/her own cadence. They are instructed to walk barefoot on the floor and trace repetitive loops along an approximately rectangular path roughly parallel to a side-way camera. Before data acquisition, subjects loop a few times until they feel comfortable that they can walk with the current setting speed. During and after each capture, if they feel unsatisfied with their performances due to the mismatch between their speeds and the desired speed, they are asked to let us know and the data are discarded and new data re-captured again. With this setup, the subjects would be the best persons to know the consistency of their walking speed compared with the graphical moving lines.

Another interesting note is about the way the guiding images are projected onto the wall. Normally, we would want to see human walking horizontally either from left to right or vice versa. In our earlier experiments, we discover that while trying to walk straight towards the wall and at the same time concentrating on the walk images moving from left to right, people tend to drift from their straight path to the right while

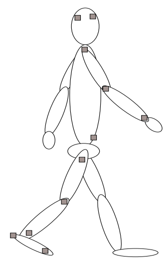

Figure 4: Landmarks where the reflective markers are attached.

they are getting close to the end of the path or close to the wall. The reason being that the perception concentrates on movement in a direction different from our current physical body movement. By rotating the images 90 degree, the projector displays the vertical walks from the bottom to the top of the image frames. This arrangement helps us avoid the undesirable effect in the horizontal cases since the vertical movement in the images is more coherent with the walking direction.

3.1 Motion capture system

Since we are interested in 3D walking data, our speed-control experiment is conducted in a motion capture room which has a defined straight walking path inside a captured volume. Gait data are acquired using a twelve-camera VICON system (Oxford Metric, Oxford, England). The data are sampled at 120 Hz. Subjects are attached retro-reflective markers to the body's landmarks using double-sided adhesive tapes as shown in figure 4.

A standard calibration procedure for this system is performed each day before the experiment. The calibration process involves placing the metal frame with reflective markers attached to it to indicate the X and Y axis in the space. A rigid bar, with two big reflective markers attached at both ends with 0.5 meter apart, is waved around within the entire capture volume. The collected data from all cameras are analyzed to calculate the 3D positions of those markers and the length between them. The standard deviation accuracy of the estimated length of those two markers needed to be around 1-2 mm, otherwise we repeat the calibration process again.

Note that our proposed setup can be incorporated into many existing experiments that want to control the walking speed. Besides 3D motion capture systems, researchers have come up with many interesting devices for measuring gait parameters, for examples, [22] propose to use an ultrasonic device to measure temporal and spatial gait parameters, or [21] collect gait data using an accelerometric device which is portable, requires little set-up time, works in various environments, and provides reliable results.

3.2 Walking data collection

There are 15 subjects (12 males and 3 females) with normal healthy condition participating in this study. They are informed the goals and procedures before taking part in this experiment. For each suit-up session, the subjects are required to walk at four different speeds (0.7, 1.0, 1.3, and 1.6 m/s). Three walking trials are captured for each speed. To verify the validity and consistency of the data, each subject is asked to suit up three times. The second suit-up session is arranged right after the first by completely removing all the markers from the subjects and reattached them. A third session takes place at least a day later. There are $15 * 4 * 3 * 3 = 540$ walking trials collected from this experiment. For each walking trial, one full walking cycle mostly in the middle of the trial is segmented. We manually go through each walk sequence and mark the points of the heelstrike of the right foot.

4 Characteristics of temporal and distance features respect to speed

General parameters specific to gait activity such as time-distance parameters are potentially measurable from images by computer vision techniques. These parameters usually include stride length, cadence, stride time, and speed. Several approaches use these features in their recognition techniques with a normal, constant speed assumption. We argue that when people change their speeds, their gait patterns do change. And it is reasonable to assume people do change their speeds. Therefore, it is necessary to understand the expected performance of these features when used in general speed conditions and how to handle them with respect to speed differences.

Since speed is related directly to stride length, cadence and stride time parameters, our speed-control data allow us to look at these parameters more closely on their relationships. Stride length and stride time can be measured directly from the 3D walking data. *Stride length* is defined as the distance between one heelstrike to the next of the right foot in the walking plane. *Stride time* is computing by dividing the number of data samples of each walk cycle by the sampling rate (120 Hz in our case). *Cadence* (strides/min) is calculated by dividing 60 seconds by a stride time (seconds).

Stride length and cadence vs. speed

Normally when people increase their walking speeds, both of their strides and cadences are adjusted accordingly. It is known that the stride length increases monotonically as walking speed increases. Several reports in the past have suggested the linear relationships between walking speed and stride length for normal population. In gait recognition, however, we need to know the relationship between these features at individual level in order to find a way to adjust, normalize, or map features across speeds for the recognition tasks.

Figure 5 shows indeed the linearity between stride length and walking speed from all trials of 15 subjects. Moreover, we can see that the fitted mean lines of the subjects have different slopes. Figure 6 shows all data from 15 subjects (left), the fitted mean lines plotted together to give us better views of the similarities and differences between individuals (middle), and the coefficients b_0 and b_1 (from the linear equation $y = b_1 * x + b_0$) of the 15 lines in the coefficient space (right). One observation about the slopes of the fitted mean lines is that if a person has a narrow stride length at small speeds,

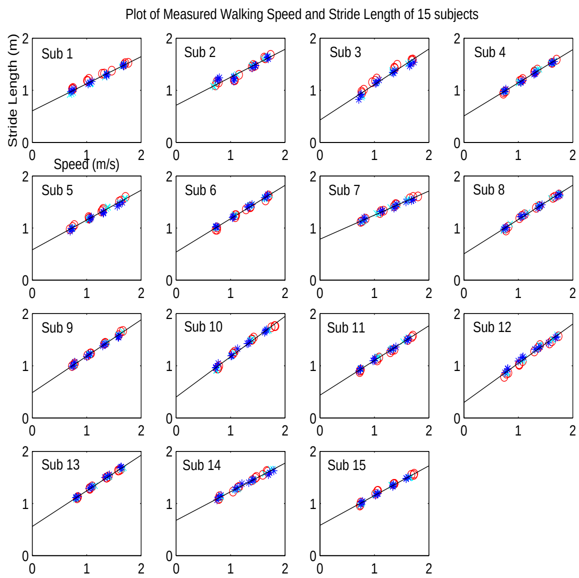

Figure 5: Linear relationships between stride length and speed of 15 subjects. For each subject, 4*3*3=36 data points are plotted and a mean line is fitted through them.

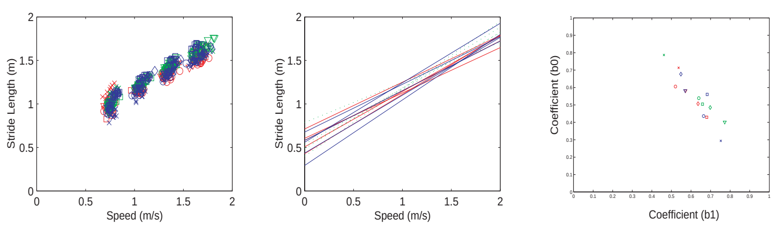

Figure 6: Left: All data from figure 5 plotted together. Middle: Individual fitted mean lines. Right: The coefficients of 15 lines.

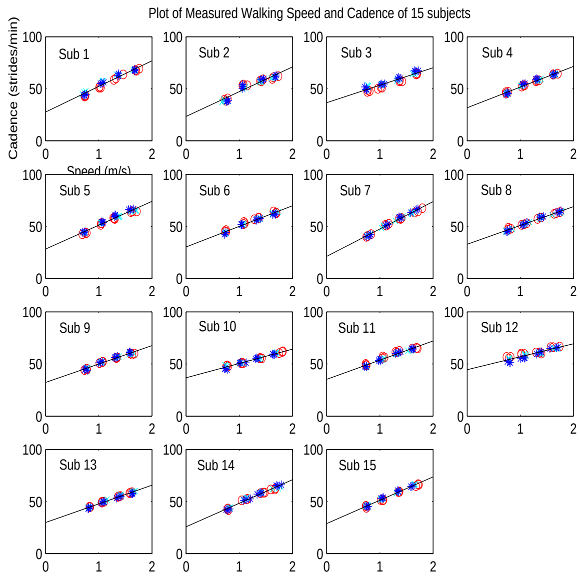

Figure 7: Linear relationships between cadence and speed of 15 subjects. For each subject, 4*3*3=36 data points are plotted and a mean line is fitted through them.

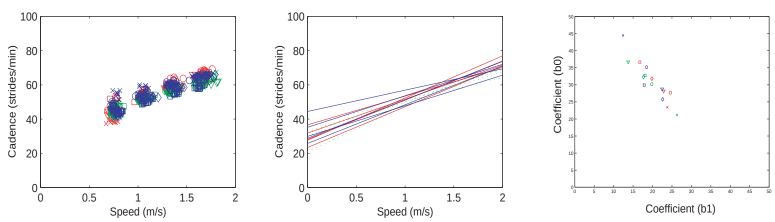

Figure 8: Left: All cadence data from 15 subjects plotted altogether. Middle: Individual fitted mean lines. Right: Distribution of the coefficients of 15 lines.

he/she has to increase stride length more at the higher speed to be able to cover a certain distance in a certain amount of time. Therefore, the slopes tend to be steeper than the slopes of those who have a wide stride length at small speed. If people do not change their gait patterns drastically, we can expect these individual fitted mean lines to represent their characteristics of the stride length feature across walking speeds. If we manage to recover the mean line of a person, we can use its coefficients to find possible matches.

Similar linear relationships can be found also in the case of *[cadence, speed]* pair (figure 7 and 8). Similar to the stride length case, if a person takes fewer number of strides at the small speed, he/she has to increase cadence more at the higher speed to be able to cover a certain distance in a certain amount of time. Therefore, the slopes tend to be steeper than the slopes of those who take many strides at the small speed.

Stride length and cadence features vary linearly when walking speed changes. The

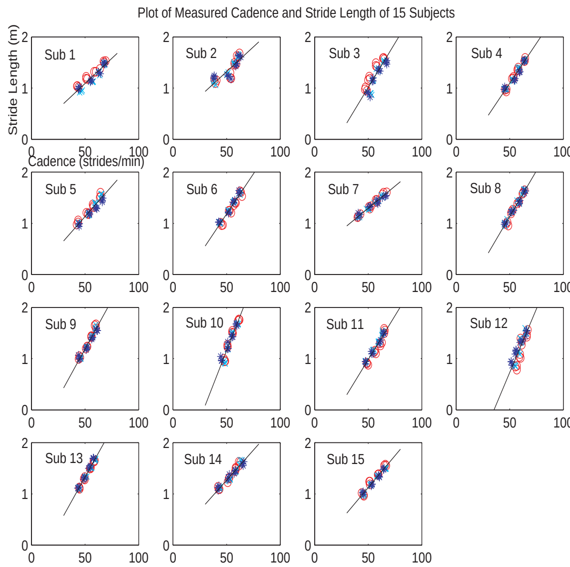

Figure 9: Linear relationships between stride length and cadence of 15 subjects. For each subject, 4*3*3=36 data points are plotted and a mean line is fitted through them.

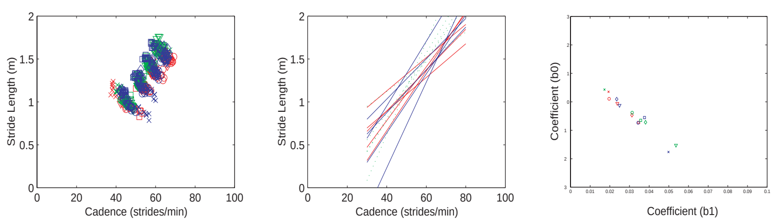

Figure 10: Left: All stride length and cadence data from 15 subjects plotted altogether. Middle: Individual fitted mean lines. Right: Distribution of the coefficients of 15 lines.

intuition is that when people walk faster, they tend to increase both stride length and cadence altogether. Figure 9 and 10 show the raw data and the fitted mean lines plotted in the same axes to give us better views of the similarities and differences between individuals. The linear relationship between these stride length and cadence can be expected since both parameters have linear relationships with speed parameter.

Stride time vs. speed

Stride time is measured as the duration a person takes to execute one walk cycle. Researchers in biomechanics and human movement study fields have also looked further into stance phase and swing phase durations. It is intuitive that the faster the walking speed, the shorter time it should take for each cycle. Figure 11 shows the stride time as a function of the speed for 15 subjects. The plots suggest the non-linear relationship. Using a hyperbola to fit the data seems appropriate. All fitted hyperbolas

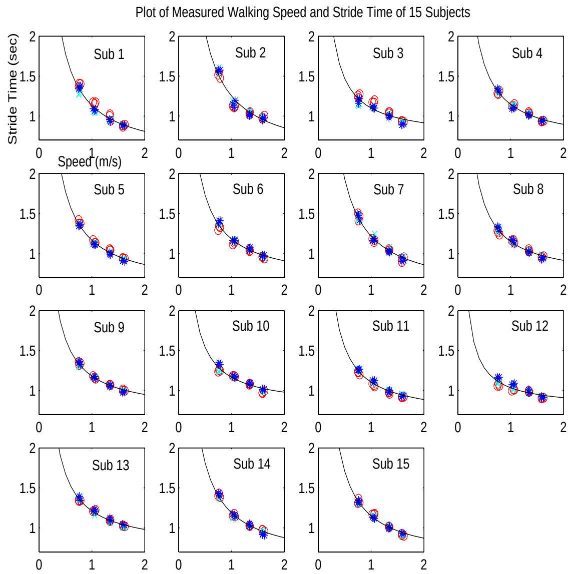

Figure 11: Stride time and speed for 15 subjects with fitted hyperbolas

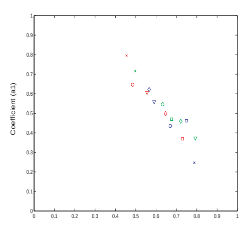

Figure 12: The distribution of coefficients a_0 and a_1 of the fitted mean lines.

are slightly different suggesting the inter-individual variations. A hyperbola curve has an equation $Y = a_1/X + a_0$. Each individual hyperbola curve has one pair of a_0, a_1 coefficients. Figure 12 shows the distribution of those coefficients in the space of a_0 and a_1.

Note that the distribution in figure 12 is very similar to the plot in figure 6 (right). The reason is that there is a straight relationship between stride length and stride time. Recall from a simple physics concept that speed (*S*) is equal to distance (*D*) divided by time (*T*).

$$S = D/T \tag{1}$$

From the linear relationship between stride length and speed, we have

$$D = b_1 S + b_0 \tag{2}$$

$$S = (b_1 S + b_0)/T \tag{3}$$

By rearranging (3) for stride time T in terms of speed S,

$$T = b_0/S + b_1 \tag{4}$$

Therefore, the hyperbola fit in the stride time case has a direct relationship with the linear fit in the stride length case. The coefficients of both cases are then closely related.

5 Summary and future work

This paper presents the details of our study of time-distance gait parameters especially stride length, cadence, and stride time across walking speeds. Our methodology in the speed-control experiment is explained in detail. We have shown the characteristics of these features at the levels of the inter- and intra-individual variations. Future work includes the investigation of using these relationships to help compensate and adjust these features across different speeds in the recognition tasks. The expected performance and usefulness of these features if used in the scenarios where people are allowed to walk at different speeds. We also want to extend the study to other types of gait parameters such as joint angles of the lower extremity for the recognition purposes.

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