

JOINT MOTION PATTERN OF LIMB MOVING MANNEQUINS FOR ACTIVE SAFETY VEHICLE TESTS

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ABSTRACT

Pre-Collision Systems (PCS) for pedestrian crash avoidance have been equipped on certain high-end passenger vehicles. At present, there is not a common evaluation standard to compare the performances of PCS for pedestrian collision avoidance. The Transportation Active Safety Institute (TASI) at Indiana University-Purdue University-Indianapolis has been studying the establishment of such a standard with support from Toyota Motor Corporation. One task surrounding the development of such a standard is the creation of mannequins that move like real pedestrians. To make a mannequin move like a human being, it should have joints at the hip, knee, shoulder and elbow and be able to plan the joint motion trajectories. The mannequins need to have standing, walking or running gestures during PCS evaluation. A cost-effective source of gaiting information is from papers published in the medical field. These papers reported the joint angle measurements of hundreds of human subjects in all age spans. However, most of the results in these papers were based on gender, age, and heuristic motion speeds. They are not directly useable in mannequin motion planning. This paper aggregates and converts the measured gaiting parameters from many publications into functions of walking/running speed for easier mannequin joint trajectory planning. Specifically, we have successfully extracted and aggregated the measured data of hundreds of subjects reported from many medical gaiting and running publications, and presented them as functions of walking speed. The functions include step size, step frequency, maximum hip flexion, maximum hip extension, maximum knee flexion at stance, maximum knee flexion at swing, and their

corresponding occurrence time as the percentage time in a step cycle. The result of this study enables the joint trajectory planning for the mannequin to be used at walking and running speeds.

1. INTRODUCTION

Pre-Collision Systems (PCS) for pedestrian crash avoidance have been equipped on certain high end passenger vehicles. At present, there is not a common evaluation standard to compare the performances of PCS for pedestrians. The Transportation Active Safety Institute (TASI) at Indiana University-Purdue University-Indianapolis has been studying the establishment of such a standard with support from Toyota Motor Corp. One task surrounding the development of such a standard is the creation of mannequins that can represent average pedestrians. Since PCS sensors detect pedestrians partially based on their body sizes and gestures, mannequins not only should be built with heights and body sizes representative of the pedestrian public, but also should be able to show major walking and running gestures. Therefore, TASI is developing limb moving mannequins that look and move like pedestrians. The design of a properly functional mannequin consists of the study of following issues: the frame structure and limb motion mechanism, the size of the mannequin and body parts, the motion ranges and timing of all joints for different walking and running speeds, the mannequin skin development, the mannequin clothing. This paper focuses on the motion ranges and timing of all joints of mannequins for different walking and running speeds.

This paper is organized as follows. Section 2 briefly describes the mannequin motion mechanisms.

Section 3 describes the method of using gait analysis data to obtain the gaiting data for mannequin. The discussion and conclusions are in sections 4 and 5 respectively.

2. BACKGROUND

For a mannequin to move like a human being, it should have the horizontal motion and limb motion. In this study, the horizontal mannequin motion is achieved by hanging the mannequin on a wirelessly controlled trolley running on a gantry crane. The limb motion is achieved by installing motors on mannequin joints. Humans use many joints to control the body motion, such as shoulder, elbow, hip, torso, knee, and ankle. However, due to the constraints in mannequin power consumption, weight, ruggedness, and the significance of each joint towards the walking and running gestures, a motor is installed on each shoulder, hip and knee, and a passive joint is used at each elbow. No joint is installed at the torso and ankle. The mannequin itself can only move limbs but cannot actually walk or run.

During PCS evaluation, scenarios with various speeds of mannequin motion are required. Since pedestrians' gait parameters change with the motion speed and the test scenarios can specify different pedestrian speeds, it is desirable to have the gait parameters described as functions of the pedestrian motion speed in order to control the mannequin motion in different test scenarios. To make a mannequin motion like an average real human from slow walking to fast running, the speed range of 0.5 to 4.3 m/s is required for the mannequin motion. Since the gait information in terms of the motion speed is not readily available, this paper describes a process to obtain the gait information from public domains.

Human gaiting data were searched in the fields of computer animation, human like robotics and biomechanics. Although there are a lot of computer simulations and animations of human beings in video games and movies, the joint motion in most of these programs are based on the artistic drawing but not based on the actual human gaiting data. There is a computer simulation program [1] that provides credible gait simulation. Some data used in this program were contributed from projects sponsored by United States National Institute of Health. The program supports 12 gait animations, each of that is developed based on one of the twelve children age from 7-12 years old. These animations provide all joint data for gait cycles of various walking speeds. Descriptions of the capability of the animation

program are in [2, 3]. The theoretical support of this animation program is described in [4, 5]. Other possible walking simulation data and publications can be found in [6-8]. The papers in the walking robot field emphasizes on robot's ability to walk [9]. The gaiting data are generated based on the physics principles and minimum energy usage without the concern of whether the walking robot walks like a human being or not. There are more measured human gaiting data in the field of biomechanics. Some studies collected real measured data from hundreds of human subjects to establish a reference walk pattern for slow, comfortable, and fast walking [11- 14]. This study is to use the data in the biomechanics field to find the joint motion trajectory of average pedestrian in United States with respect to motion speed. The result is divided into four parts: adult walking, adult running, children walking, and children running.

3. PEDESTRIAN MANNEQUIN MOTION PATTERN

3.1 Adult Walking

Two comparable gait measurement studies were conducted in US [10] and Sweden [11, 12] respectively. The gaiting parameters of 260 subjects were measured in US and that of 233 subjects were measured in Sweden. The ages of subjects were from 10 to 79 years old. This amount data is desirable since it can represent the gaiting data for average pedestrians. However, all data in these two studies are grouped based on subjects' ages and three subject interpreted speeds in terms of slow, comfortable and fast. Since PCS detects pedestrians based on their sizes and gestures but not based on ages, the data useful for PCS evaluation should be rearranged to remove the age information and to relate to motion speed information. Fortunately, this data rearrangement is feasible since all subjects described in these papers were required to walk in slow, comfortable and fast speeds interpreted by each subject. Since the interpretation of slow, normal, and fast are different among different subjects, the gait data collected in these two studies covers the spectrum of walking speed in the range from 0.6 m/s to 2.4 m/s. Step sizes and step frequency data in these papers are rearranged and plotted in terms of motion speed (see Figure 1). Each point in Figure 1 represents the data of one age group at one walking condition in one paper. It is well known that the product of step size and the step frequency is the motion speed. Therefore, the product of step size and the step frequency of the same subject group in terms of motions speed is plotted in order to check the

quality of the data (see Figure 2). The linear equation generated by curve fitting shows that this plot is a straight line with slope 1.06 which demonstrated that data is accurate. Quadratic functions of the step size and step frequency in respect to the motion speed (see Figure 2) are generated using best fit functions.

Since the height of our adult mannequin is selected as 168 cm which is close to the average height, 169cm, of US adults (including all ages), we assume that the average height of about 520 subjects shown in [10, 11] is close to the average pedestrian of 169 cm tall. Therefore, based on the step size – motion speed equation and step frequency-motion speed equation, the step size and step frequency of the adult

mannequin at different walking speeds can be calculated. Additional measured gaiting data of more than 250 human subjects can be found in [13, 15, and 16]. These gaiting measurement data can be added to the plot in Figure 2 to generate more statistically accurate gaiting functions.

After obtaining the step size and step frequency of mannequin gaiting, the next step is to find the corresponding joint angles in each gait cycle. The first question is that how many joint angles in each gait cycle are needed. In theory, the more control points used in a cycle, the more realistic motion can be generated. However, the challenge is to be able to find data for all angles in a gait cycle.

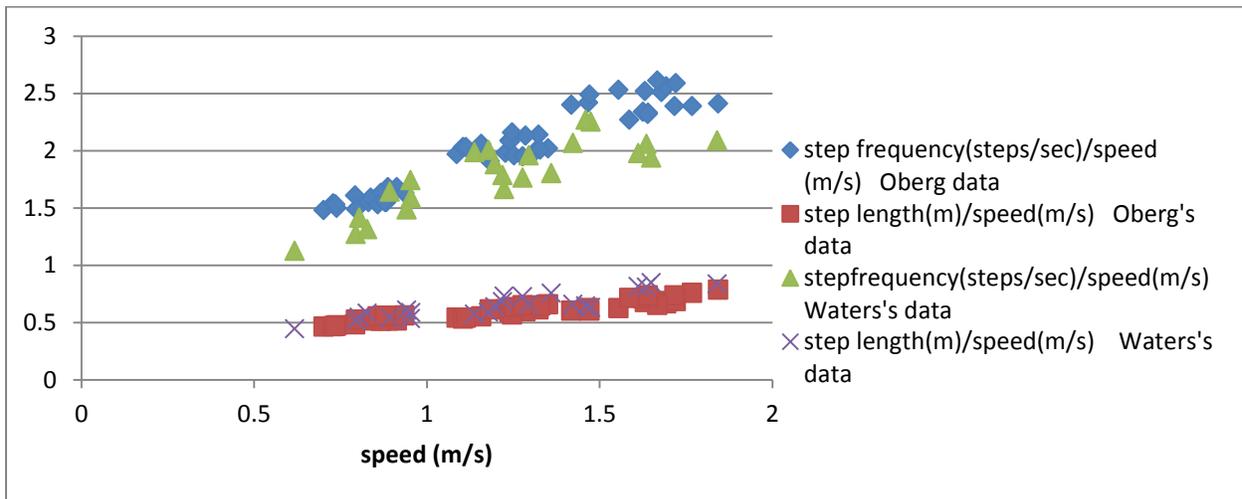


Figure 1. Compare step sizes and cadences in two different studies.

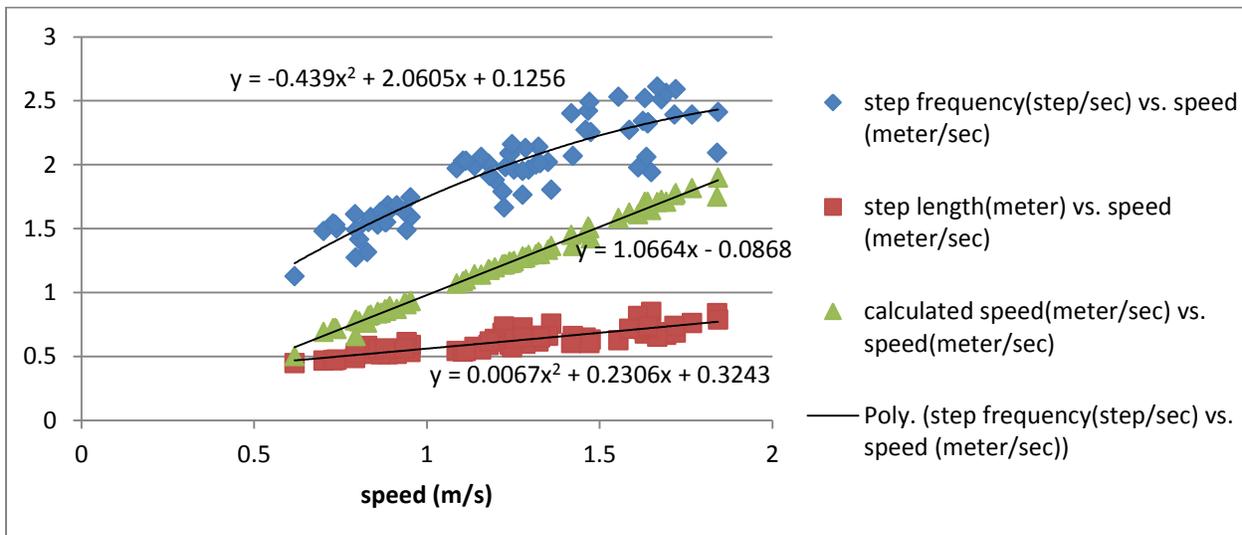


Figure 2. Functions of step size (m) and step frequency (steps/sec) in vertical axes respect to walking speed (m/s) in horizontal axis.

By analyzing the gait cycle, it is decided to use the joint angles where the joint changes the motion directions. Therefore, the joint angles of interest include two extrema angles for the hip motion, two extrema angles for the shoulder motion, and four angles for the knee motion in each gait cycle. Figure 3 shows the four angles of the knee joints at which the knee angular velocity changes the direction.

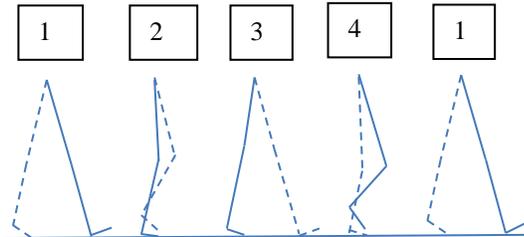


Figure 3. The hip and knee joint angles essential for mannequin gaiting control. For legs shown in solid lines, 1= heel contact, 2= mid-stance, 3= hell-off, 4= mid swing.

The angular velocity of the hip changes the direction only at heel contact location and the heel off location. The angular velocity of the knee changes the direction at all four locations. The extrema hip joint angles are at the maximum flexion and the maximum extension (solid leg in 1 and 3 of Figure 3 respectively). The interested knee joint angles are at heel contact, mid stance, heel off, and mid swing gestures 1 to 4 in Figure 3, respectively). It is assumed that knee angles at both heel contact and heel off positions relative to the thigh are zero in walking. Knee angles at mid stance and mid swing are the maximum flexion where joint motion

direction changes. Most gait measurement data includes hip flexion/extension and knee flexion.

Once the extrema joint angles at different walking speed are known, the next question is when do joints reach the extrema angles. Many papers presented the timing of joint angles as the percentages of a gait cycle (%cycle). Figure 4 is a maximum hip flexion figure copied from [17]. Stars are added on the top of the curve showing the maximum hip flexion and on the bottom of the curve showing maximum hip extension with respect to the corresponding % gait cycle. Figure 5 is a modification of another figure in [17] that demonstrates the left knee and right knee angles of interest (marked by stars) corresponding to %gait cycle. The 0% of the right knee is aligned with 50% of the left knee in a gait cycle. Since the % gait cycle of each star point changes as walking speed changes, the next step is to find how the % gait cycles of the star points change as motion speed changes.

Although [12] provided a linear approximation of the knee and hip extrema angles with respect to motion speed (copied to the lower three cells of the middle column of Table 1, the timing of reaching the angles is not shown in [12]. This information is derived from the data provided in [18]. [18] is a survey paper that thoroughly summarized 83 gaiting publications. [18] also showed the gait timing of the extrema joint angles in terms of %cycles with four different motion speeds (walk (1.2 m/s), run (3.2 m/s), sprint (3.9 m/s), elite sprint (9 m/s)). By curve fitting these %cycles values of each extrema joint angle at 4 different speeds, we obtained the time corresponding each extrema angle with respect to motion speed (see right column of Table 1).

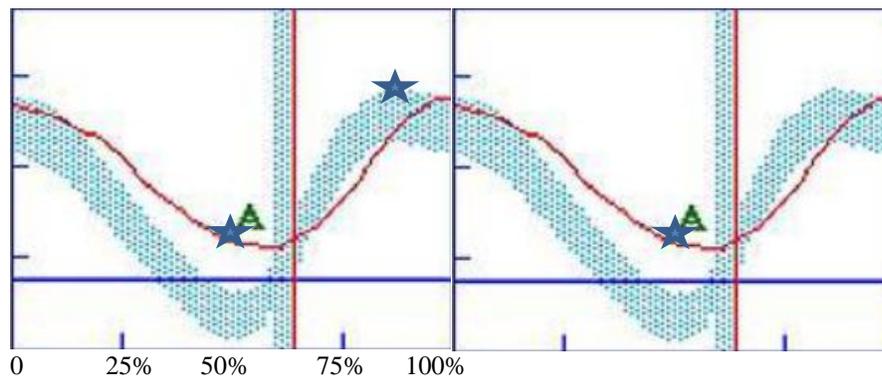


Figure 4. Hip angles with respect of the % of a gait cycle.

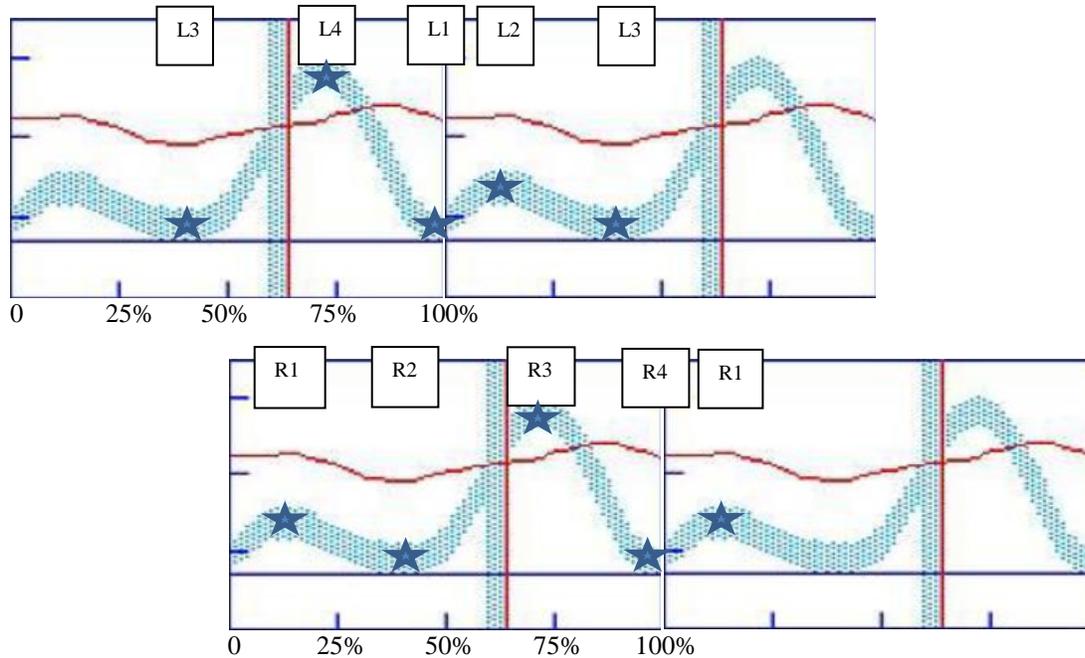


Figure 5. Knee angles with respect of the % of a gait cycle. L1 to L5 are the joint angles and time of consecutive left knee joints. R1 to R5 are the joint angles and time of consecutive right knee joints.

Table 1 is the summary of the gait parameter calculation for adult mannequin

	Equation(related to speed X in cm/sec)	Extreme at cycle percentage(related to speed X in cm/sec)
Step Size (m)	$0.0067*X^2 + 0.2306*X + 0.3243$	
Step Frequency (m/s)	$-0.439*X^2 + 2.0605*X + 0.1256$	
Hip Flexion/ Extension (degrees)	Flexion – Extension : $27.8+0.16*X$	Flexion: $0.5298*X^2 - 8.3022*X + 103.87$ Extension: $0.3272*X^2 - 5.6556*X + 57.385$
Knee Stance (degrees)	Flexion – Extension: $1.25+0.135*X$	Flexion : $0.2116*X^2 - 2.9312*X + 43.213$ Extension : $-1.0714*X^2 + 5.4643*X + 5.9857$
Knee Swing (degrees)	Flexion – Extension: $56.7+0.068*X$	Flexion : $-0.0994*X^3 + 1.4069*X^2 - 7.6479*X + 79.323$ Extension : $0.2384*X^2 - 2.5343*X + 100.53$

3.2 Adult Running

[18] presented the functions of step length, step frequency, hip angle and knee angle with respect to one specific speed of walking, one specific speed running, and one specific speed sprinting, respectively. The data in [18] also presented joint extrema in these 4 different speeds in respect of percentage of a motion cycle. Here we rearrange the data by curve fitting each extreme joint angle at these 4 given speeds and mapping the joint angles and the %cycle time respect to the motion speed. Therefore we can derive the joint angles and %cycle time for a

specific adult running speed using these functions. Figure 6 shows step length, step frequency (cadence), stride time (2 steps) and non-support (foot off-ground time) functions in terms of the running speed. Figure 7 shows four knee flexion/extension extrema angles with respect to the running speed. Figure 8 shows %cycles at which the extrema knee flexion/extension occur with respect to the running speed. Figure 9 shows two thigh extrema position in terms of running speed. Figure 10 is the %cycle values at which two thigh extrema occur in a running cycle. Table 2 summarizes the extrema joint angles and their corresponding %cycles.

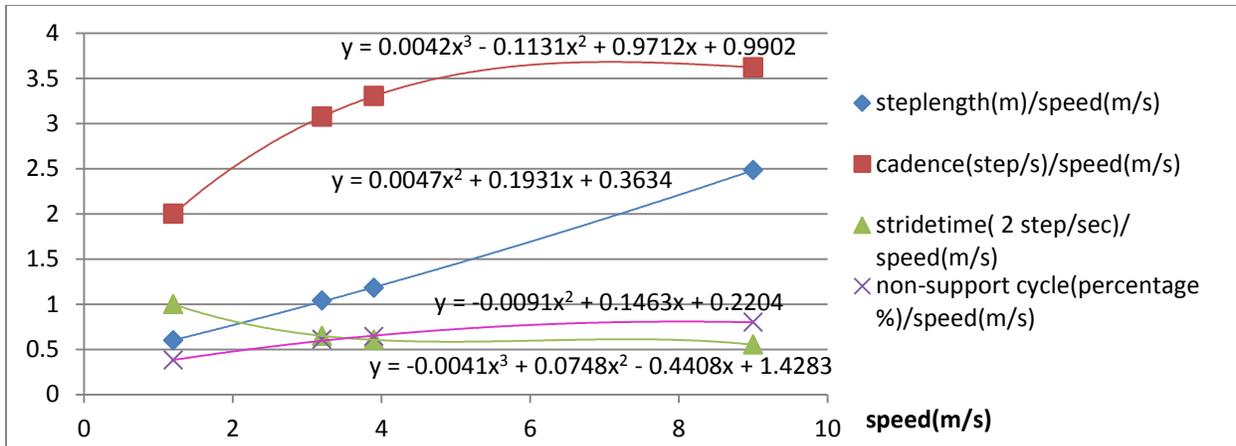


Figure 6. Adult running step length (m) and step frequency (steps /s) vs. running speed (m/s).

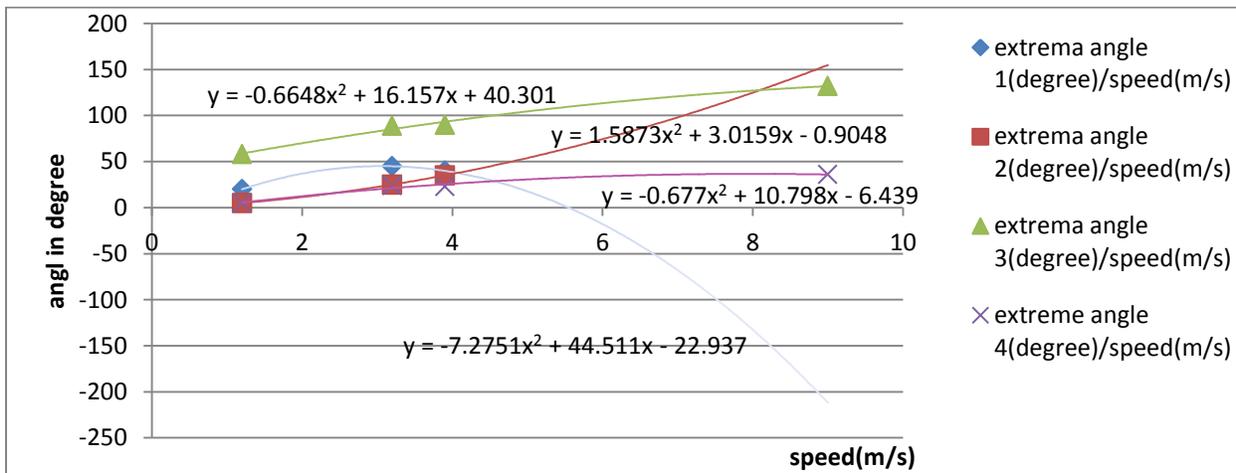


Figure 7. Adult knee angle vs. speed.

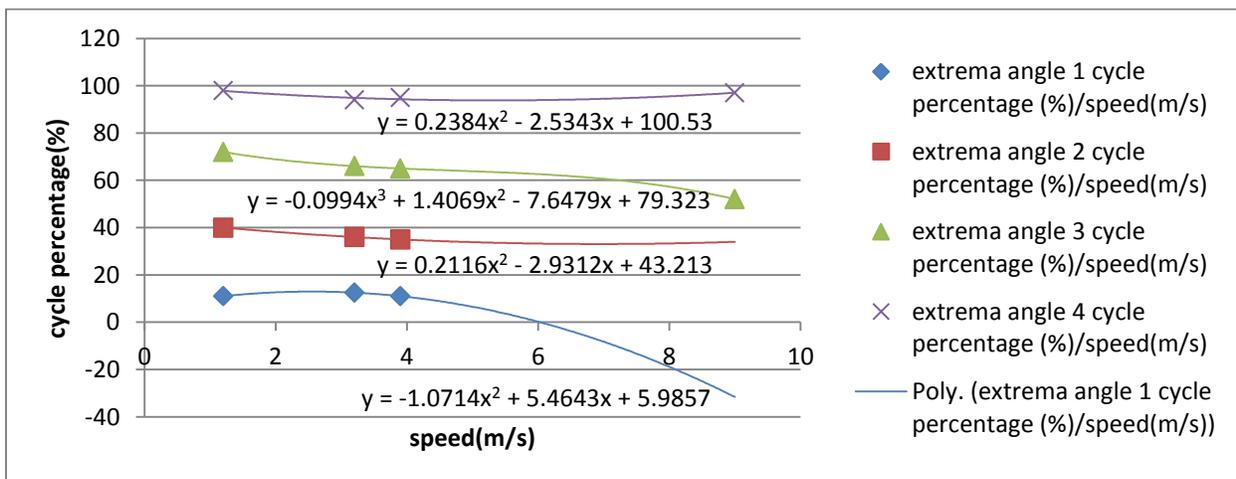


Figure 8. Adult knee %cycle vs. running speed.

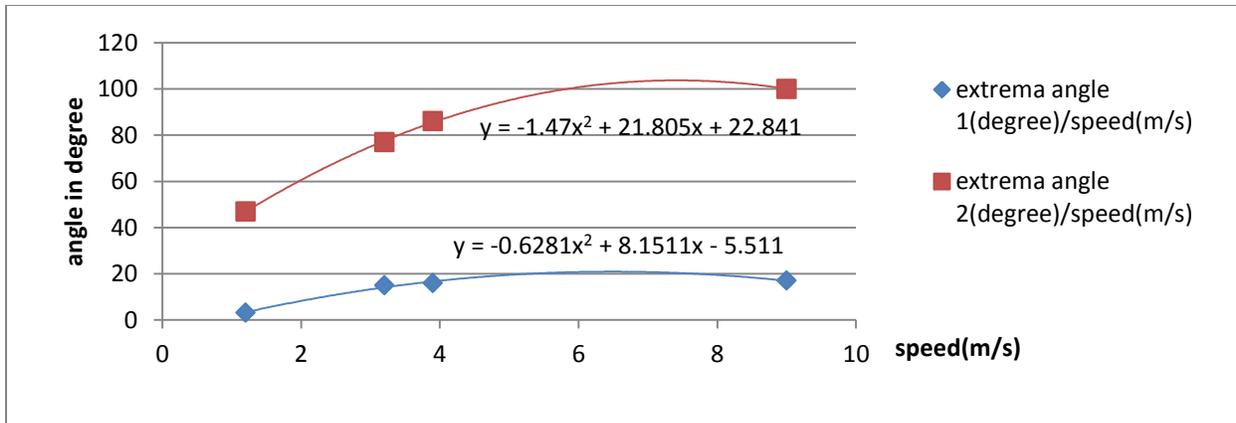


Figure 9. Adult thigh angle vs. running speed.

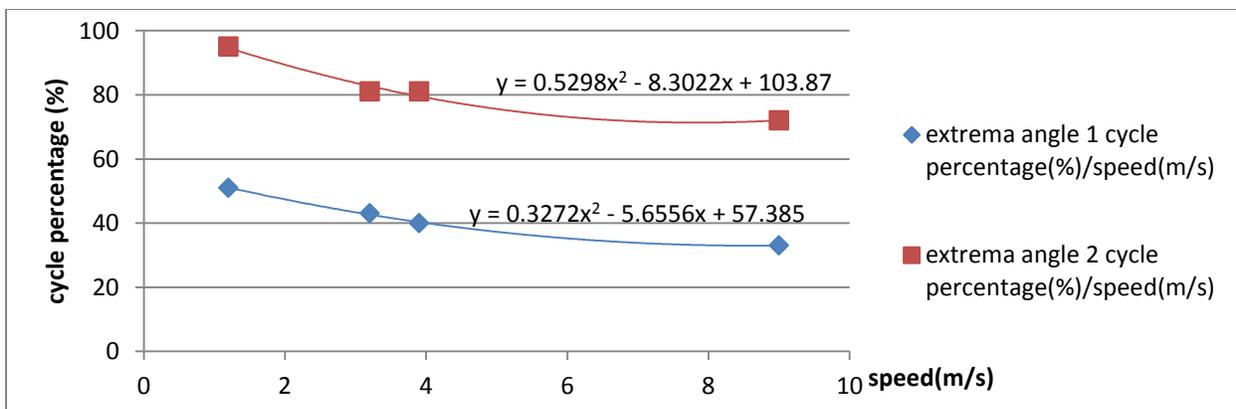


Figure 10. Adult thigh %cycle vs. running speed.

Table 2. Mannequin motion control parameters for adult running

	Equation (related to speed X in m/sec)	Extreme %cycle (related to speed X in m/sec)
Step Size (m)	$0.0047X^2 + 0.1931X + 0.3634$	
Step Frequency (steps/s)	$0.0042X^3 - 0.1131X^2 + 0.9712X + 0.9902$	
Thigh position (femur relative to vertical, degrees)	Flexion: $-1.47X^2 + 21.805X + 22.841$ Extension: $-0.6281X^2 + 8.1511X - 5.511$	Flexion: $0.5298X^2 - 8.3022X + 103.87$ Extension: $0.3272X^2 - 5.6556X + 57.385$
Knee Stance (degrees)	Flexion: $-7.2751X^2 + 44.511X - 22.937$ Extension: $1.5873X^2 + 3.0159X - 0.9048$	Flexion: $0.2116X^2 - 2.9312X + 43.213$ Extension: $-1.0714X^2 + 5.4643X + 5.9857$
Knee Swing (degrees)	Flexion: $-0.6648X^2 + 16.157X + 40.301$ Extension: $-0.677X^2 + 10.798X - 6.439$	Flexion: $-0.0994X^3 + 1.4069X^2 - 7.6479X + 79.323$ Extension: $0.2384X^2 - 2.5343X + 100.53$

3.3. Children Walking

The same approach was tried to find the joint angles and occurring timing for children as that for adult walking. However, there is very limited number of publications related to children gaiting. [14] provided the measured walking step lengths and cadences of

20 Brazilian children from 3 to 6 years old, which is plotted with respect to walking speed in Figure 11. The functions of step length and step frequency with respect to walking speed are generated using least mean square curve fitting. No joint angle information measured in the study reported in [14]. [19] provided the hip and knee extrema angles of 28 children of 5-6

years old at a specific walking speed and also provided the timing of the joint angle changes. [20] provided the measured gait parameters of 16 children during their growth from 7 to 12 years for 5 consecutive years, and provided detailed knee maximum swing flexion, stance flexion, and hip flexion/extension with respect to % gait cycles. [1] provides credible gait simulation because the data used in the program is contributed from projects sponsored by National Institute of Health. The program supports 12 gait animations each of which is developed based on one of the twelve children age from 7-12 years old. These animations provide all joint data for gait cycles of four different walking speeds. In summary, since the height and the leg length of children vary significantly from 5 to 12 years old, the available data is not sufficient to draw conclusion on how a representative six years old

child (average 108 cm tall) walks. However, the available data in above referenced publication allow us to find the measured gaing data of at least one child of specific height for a given walking speed.

3.4 Children running

[14] also provided the measured running step lengths and cadences of 20 Brazil children from 3 to 6 years old which is plotted with respect to running speed in Figure 12. The functions of step length and step frequency with respect to running speed are generated using least mean square curve fitting. However, joint angles and timing were not measured in the study reported in [14]. More data search need to be conducted to find the children running information.

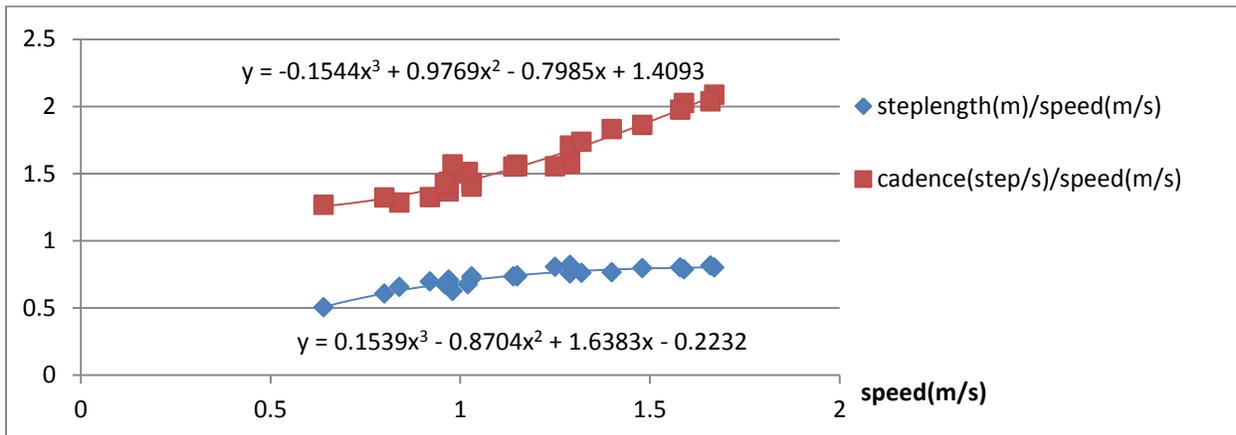


Figure 11. The relationship of cadence and step length with respect to walking speed for 20 Brazil children from 3 to 6 years old (the unit of the speed is m/s and the unit of the step length is meter).

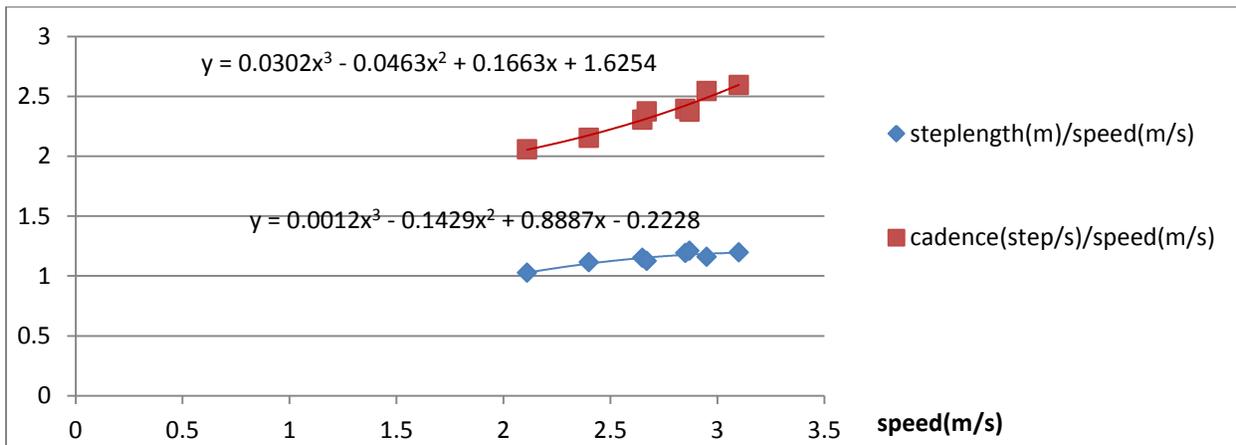


Figure 12. The relationship of cadence and step length with respect to running speed for 20 Brazil children from 3 to 6 years old (the unit of the speed is m/s and the unit of the step length is meter).

4. DISCUSSION

We did not find the biomechanics publications containing the measured shoulder and elbow joints data. Since the arm motion is to counterbalance the body rotation caused by leg motion, we will use the same hip joint trajectory data (frequency, angle and timing) on the opposite shoulder.

5. CONCLUSIONS

We extracted and aggregated the measured data of hundreds of adult subjects reported from many medical gaiting and running publications, and presented them as functions of walking speed. The functions include step size, step frequency, maximum hip flexion, maximum hip extension, maximum knee flexion at stance, maximum knee flexion at swing, and their corresponding occurrence time as the percentage time in a step cycle. There is very limited data for obtaining the representative data for children but there is gaiting data for child mannequin to mimic the gait motion of individual child at specific walking speed. The result of this study enables the joint trajectory planning for the adult mannequin at walking and running speeds.

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