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ORIGINAL ARTICLE

Modelling of the toe trajectory during normal gait using circle-fit approximation

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Abstract This work aimed to validate the approach of using a circle to fit the toe trajectory relative to the hip and to investigate linear regression models for describing such toe trajectories from normal gait. Twenty-four subjects walked at seven speeds. Best-fit circle algorithms were developed to approximate the relative toe trajectory using a circle. It was detected that the mean approximation error between the toe trajectory and its best-fit circle was less than 4 %. Regarding the best-fit circles for the toe trajectories from all subjects, the normalised radius was constant, while the normalised centre offset reduced when the walking cadence increased; the curve range generally had a positive linear relationship with the walking cadence. The regression functions of the circle radius, the centre offset and the curve range with leg length and walking cadence were definitively defined. This study demonstrated that circle-fit approximation of the relative toe trajectories is generally applicable in normal gait. The functions provided a quantitative description of the relative toe trajectories. These results have potential application for design of gait rehabilitation technologies.

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Keywords Toe trajectory · Normal gait · Circle-fit approximation · Rehabilitation robotics

1 Introduction

Increasing our knowledge of human gait biomechanics is an important step towards developing robotics for walking rehabilitation. In order to provide proprioceptive input during gait rehabilitation in people with an impaired gait pattern, exoskeleton-based gait orthoses actuate the joints of the lower limbs directly in a way that is similar to normal gait [2]. A representative gait exoskeleton is the Lokomat [8], which moves the hip and knee joints with electric motors in a gait-like pattern. Other lower limb robotics focus on the foot trajectory to indirectly ensure proper gait, based on the end-effector principle [3, 20]. A typical end-effector gait orthosis is the G-EO system, which guides the foot motion directly so as to obtain a normal walking pattern in the lower limbs [7]. The lower limb is often considered as a three-segmental linkage [5]. If the end-point, i.e. the foot, or rather, the toe, is well controlled, the hip, knee and the ankle joints will then move as in normal gait. This was demonstrated in our previous simulation work [4]. In the end-effector scheme, the toe trajectory relative to the hip provides a direct reference profile for the control strategy.

Although extensive research has investigated the kinematics of human walking, the characteristics of the toe trajectories in normal gait are not as yet well understood. Winter et al. performed several limb biomechanics studies on leg movements during normal gait [16, 22]. Winter [22] investigated the foot motion when eleven subjects walked at slow, natural and fast cadences. He analysed in detail the influence of joint movement and muscle performance in the lower limb on the toe trajectory and finally concluded that the foot movement was a precise end-point control task [22]. Toe trajectories were also investigated in studies on the foot tripping problem during walking. The foot clearance, which is the distance between the floor and the lowest point on the swing leg foot, was widely analysed in healthy populations [1] and patients [13], young and old persons [14], walking in different terrains [17], or performing different tasks during walking [18]. Restricted by their individual research foci, these studies only analysed the toe trajectory in the swing phase. It was considered that the swing toe trajectories were influenced in a complex way by factors including height, age and the toe-off control strategy [15]. The toe trajectory during the whole gait cycle is presented in studies [12, 16, 22, 23], but relative to the ground, rather than relative to the hip joint centre. To adopt the end-effector control approach for gait robotics development, the toe trajectory relative to the hip joint centre is of great importance.

The toe trajectory relative to the hip within the whole gait cycle was analysed in our previous feasibility study [6], but further research is required. Investigating the pendulum property of normal gait, our previous study [6] revealed that the toe trajectories relative to the hip were curved and could be well fitted by part of a circle. The best-fit circle had its centre forward of the hip joint, and the radius was approximately equal to the leg length. As a feasibility design, our previous study [6] recruited only three able-bodied subjects to walk at three different speeds. As a consequence, the toe trajectories based on relatively few walking trials were analysed. For a generalised application of using a circle to approximate the toe trajectory, it is instructive to investigate the regression function of the circle parameters to model the general toe movements during normal walking at various speeds from a larger population.

The present work aimed: (1) to validate the circle-fit approximation of the toe trajectory relative to the hip using gait data from more subjects and (2) to investigate regression models for describing the toe trajectories relative to the hip. Efficient modelling of the toe trajectory has potential application for design of gait rehabilitation technologies.

2 Materials and methods

2.1 Gait analysis experiment

A gait experiment was performed using a Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) in Ruijin Hospital, Shanghai Institute of Orthopaedics and Traumatology, Shanghai, China. Ethical approval (No. 2013023) was obtained from the Ethics Committee at Med-X Research Institute, Shanghai Jiao Tong University, Shanghai, China. All subjects provided written informed consent prior to participation.

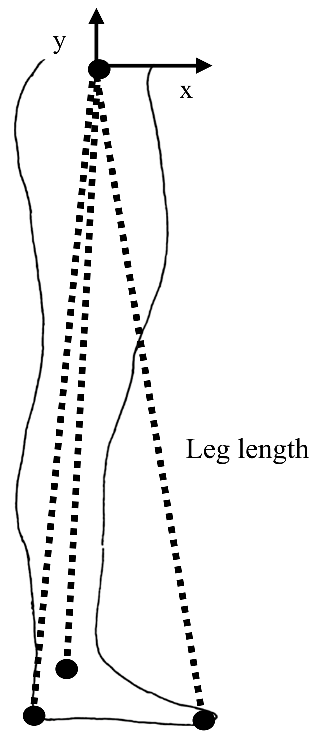

Fig. 1 Marker setup on the foot. *Black dots* at the lateral malleolus, calcaneus and second metatarsal head indicate the markers on the ankle, heel and toe, respectively. The distance from the hip centre to the toe is defined as the leg length in this study

The experimental set-up consisted of a ten-camera Vicon MX13 motion capture system (Vicon Peak, Oxford, UK). Thirty-nine reflective markers (14 mm in diameter) were affixed to specific anatomical landmarks (Plug-In Gait Marker Set, Vicon Peak, Oxford, UK) to record the segmental trajectories with a sampling frequency of 100 Hz [9]. The markers on the foot are shown in Fig. 1. The toe marker was placed on the second metatarsal phalangeal joint.

As previous research showed that the toe movements are sensitive to height, age and walking speed [15], the toe trajectories from subjects from large height and age range walking at various speeds were investigated. Twenty-four able-bodied subjects, 14 males and 10 females, height ranging from 1.53 to 1.90 m (1.69 ± 0.10, mean ± SD), age from 18 to 63 years (38.4 ± 14.5) and body mass from 48 to 94 kg (65.5 ± 11.5), were recruited to walk at seven different speeds (Table 1). The anthropometric data such as body mass, height and segmental length were measured when the subjects were in the upright standing still position. Following the definition from our previous study [6], the leg length in this study was defined as the distance from the anterior superior iliac spine to the ipsilateral toe. Each

Table 1 Height, age, leg length, normal cadence (NC) and four of the seven walking speeds for all subjects

Subject	Height (m)	Age (years)	Leg length (m)	NC (steps/min)	Speed at 0.6 NC (m/s)	Speed at 0.8 NC (m/s)	Speed at 1.0 NC (m/s)	Speed at 1.2 NC (m/s)
S1	1.53	60	0.83	110	0.38	0.63	0.85	1.16
S2	1.55	45	0.83	106	0.44	0.69	0.93	1.18
S3	1.55	47	0.83	100	0.42	0.66	0.87	1.32
S4	1.57	54	0.83	104	0.45	0.69	1.16	1.28
S5	1.58	51	0.88	112	0.55	0.84	1.06	1.42
S6	1.60	29	0.89	108	0.38	0.70	1.00	1.47
S7	1.61	40	0.87	104	0.39	0.65	0.93	1.45
S8	1.61	51	0.85	100	0.43	0.61	1.00	1.17
S9	1.64	32	0.84	110	0.42	0.67	1.16	1.58
S10	1.65	62	0.89	114	0.58	1.04	1.33	1.70
S11	1.66	24	0.90	105	0.47	0.70	1.12	1.66
S12	1.66	50	0.90	110	0.59	0.79	1.09	1.48
S13	1.67	29	0.91	100	0.33	0.59	0.93	1.19
S14	1.68	29	0.87	100	0.38	0.58	0.95	1.35
S15	1.72	22	0.93	105	0.46	0.74	1.20	1.84
S16	1.73	24	0.88	111	0.43	0.75	1.28	1.55
S17	1.74	24	0.95	104	0.5	0.80	1.16	1.50
S18	1.74	63	0.93	110	0.47	0.86	1.02	1.51
S19	1.77	28	0.95	98	0.54	0.79	1.27	1.50
S20	1.81	27	0.96	106	0.50	0.74	1.20	1.45
S21	1.81	31	1.00	94	0.46	0.85	1.31	1.63
S22	1.83	26	1.01	108	0.50	0.80	1.12	1.78
S23	1.89	18	1.06	102	0.60	0.86	1.33	1.47
S24	1.90	56	1.09	104	0.55	0.89	1.22	1.87
Mean ± SD	1.69 ± 0.1	38.4 ± 14.5	0.91 ± 0.07	105.2 ± 4.97	0.47 ± 0.07	0.75 ± 0.11	1.10 ± 0.15	1.48 ± 0.20

subject firstly chose their preferred normal walking speed. The cadence under these circumstances was recorded by a metronome as his/her normal cadence (NC). Then, we set the walking beats from the metronome as 0.6, 0.7, 0.8, 0.9, 1.0, 1.1 and 1.2 times their individual NC. The subjects were then asked to walk barefoot along a 10-m walkway following the predefined walking beats so as to walk at seven different speeds. Each walking speed was repeated three times, resulting in 504 walking trials.

2.2 Best-fit circle approximation algorithms

The approximation algorithms developed in our previous study [6] were used to search for the best-fit circle. A reference system was defined with centre (0, 0) at the hip joint. It was assumed that the toe trajectory relative to the hip joint centre had Q data points (x_i, y_i) $(i = 1, 2, 3 \ldots Q)$ within one gait cycle. The best-fit circle was determined by solving

$$f(x_i, y_i) = \sum_{i=1}^{Q} \left(\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} - r \right)^2; \quad (i = 1, 2, 3 \ldots Q) \tag{1}$$

where (x_c, y_c) is the fit circle centre and r is the circle radius. However, this is a nonlinear problem, so a modified least squares criterion $F(x_i, y_i)$ was used here [10]:

$$F(x_i, y_i) = \sum_{i=1}^{Q} \left((x_i - x_c)^2 + (y_i - y_c)^2 - r^2 \right)^2; \quad (i = 1, 2, 3 \ldots Q). \tag{2}$$

Therefore, this study searched for the values of x_c, y_c and r satisfying $\min_{x_c, y_c, r} F(x_i, y_i)$. The first derivative of Eq. (2) over r, x_c and y_c yields:

$$\mathrm{d}(F(x_i, y_i))/\mathrm{d}r = 0 \tag{3}$$

$$\mathrm{d}(F(x_i, y_i))/\mathrm{d}x_c = 0 \tag{4}$$

$$\mathrm{d}(F(x_i, y_i))/\mathrm{d}y_c = 0 \tag{5}$$

Our previous study [6] demonstrated that the centre of the best-fit circle was located at the same height of the hip joint, but horizontally forward with offset. Therefore, we obtained $y_c = 0$. Furthermore, radius r was approximately

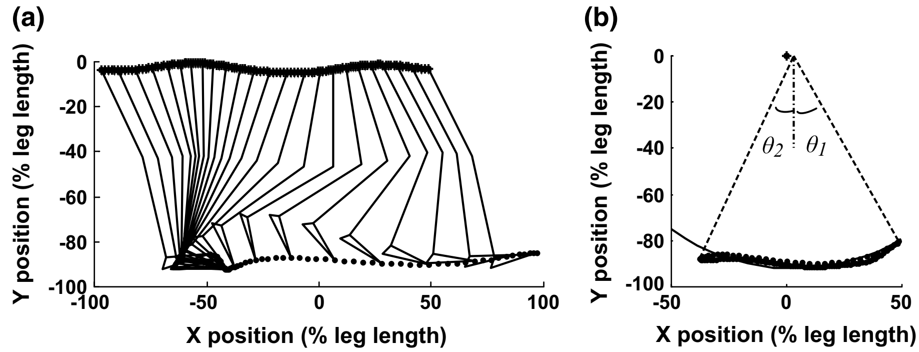

Fig. 2 Toe trajectory of a representative subject (S6) walking at her NC. **a** The trajectory relative to the ground. The *solid lines* show the leg. The *stars* at the *top* are the moving path of the hip joint centre, while the *points* at the *bottom* mark the toe trajectory relative to the ground. **b** The trajectory relative to the hip. The *star* at the *top* is the hip joint centre, while the *points* at the *bottom* mark the toe trajectory relative to the hip (the relative toe trajectory). The *solid curve* shows part of the best-fit circle. Angles θ_1 and θ_2 are the forward and backward angles

equal to the leg length. For the y coordinate of the circle at the hip ($y_c = 0$), we search for the optimal x_c and r. Equations (3)–(4) yield:

$$-4r\sum_{i=1}^{Q}[(x_i - x_c)^2 + y_i^2 - r^2] = 0 \tag{6}$$

$$-4\sum_{i=1}^{Q}(x_i - x_c)[(x_i - x_c)^2 + y_i^2 - r^2] = 0 \tag{7}$$

Solutions of Eqs. (6)–(7) gave the best-fit circles. The error was calculated as

$$E = \frac{1}{Q}\sum_{i=1}^{Q}\left|\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} - r\right|; \quad (i = 1, 2, 3 \ldots Q). \tag{8}$$

These algorithms were applied to the toe trajectories relative to the hip joint centre during walking at various speeds. For ease of comparison, the errors and the parameters related to the best-fit circle were normalised by their leg length (% leg length) [19]. The best-fit circle approximation was considered validated if the mean error [Eq. (8)] was <5 %.

In the circle approximation context, the length of the toe trajectory could be described by the curve range, which is presented by the forward and backward angles, θ_1 and θ_2 (Fig. 2b). The forward angle θ_1 was defined as the angle between the line connecting the maximal horizontal toe position and the best-fit circle centre and the vertical line. The backward angle θ_2 was defined as the angle between the line connecting the minimal horizontal toe position and the best-fit circle centre and the vertical line.

3 Results

Preferred normal cadence ranged from 94 to 114 steps/min (Table 1). Walking speeds at NC varied from 0.85 to 1.33 m/s. The overall speeds for all subjects walking at seven different cadences ranged from 0.33 to 1.87 m/s. The mean speeds during walking at 0.6 and 1.2 NC were about 40 and 135 % of the speed walking at 1.0 NC (Table 1).

Within one gait cycle, the hip joint centre oscillated rhythmically relative to the ground (Fig. 2a). The vertical displacement of the hip centre from a representative subject S6 was 4 % of leg length. In contrast, the stance toe was on the ground, while the swing toe had a complex path (Fig. 2a). As described in [1, 15], the swing toe trajectory had three peaks. The first peak fell at the early swing phase, which was 5 % of leg length above ground. The second peak, which is called the toe clearance, occurred during the mid-swing phase and was 2 % of leg length above the ground. The last peak was found at heel strike, which was 7 % of leg length above ground. In contrast to the complex toe trajectory relative to the ground, the toe trajectories relative to the hip had similarly curved stance and swing phases (Fig. 2b). Regarding the toe trajectory relative to the hip from subject S6 walking at her normal cadence, the best-fit circle had a radius equal to 93 % of her leg length, with centre 4 % horizontally displaced from the hip joint centre (Fig. 2b). The mean error between the toe trajectory and the best-fit circle was 2.3 % of her leg length.

When the walking speed was lower, the toe trajectories relative to the hip joint centre became gradually shortened (Fig. 3). We observed that the toe trajectories from older people (Fig. 3b) had larger standard deviations than those from younger people (Fig. 3a). In spite of this, the toe

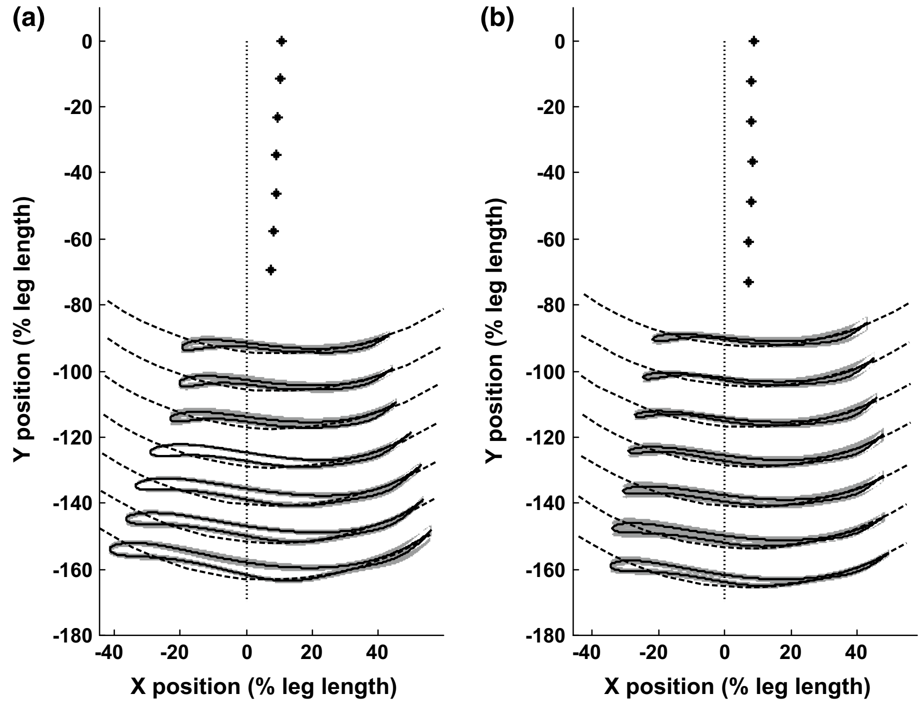

Fig. 3 Mean relative toe trajectories (*solid lines*) of two subjects (S11, S1) walking at seven different speeds. The standard deviations are presented as *shaded areas*. With the hip joint centre at (0, 0), the vertical displacements of all the toe trajectories should be within the range of −80 to −100 %. For ease of comparison, the toe trajectories at 0.7–1.2 NC are consecutively displaced lower in the graphic. From the *top* to the *bottom*, the *solid curves* are the toe trajectories at 0.6–1.2 NC. The *dashed curves* are part of their corresponding best-fit circles, with the *circle centres* marked with *stars*. The *dotted line* shows where the hip joint centre is located and divides the relative toe trajectories into two parts: **a** subject S11; **b** subject S1

trajectories relative to the hip joint centre were also curved. Similar to the relative toe trajectory from walking at NC (Fig. 2b), the best-fit circles for the relative toe trajectories from various speeds still had radii similar to the leg length, but the centres were scattered on the right side of the hip joint centre (Fig. 3).

Using the best-fit circle approximation algorithms, we obtained the circle curves for the relative toe trajectories from all subjects walking at seven different speeds. Comparison of all the relative toe trajectories and their corresponding best-fit circle curves demonstrated that the mean error increased with the walking speed (Fig. 4). Nevertheless, the mean error was always <4 %.

The mean circle radius and centre offset of the best-fit circle for the relative toe trajectory for all subjects walking at seven different speeds are presented in Fig. 5a, b. The radius varied little around 92.8 % leg length for all subjects (Fig. 5a), no matter how fast the speed was. From Fig. 3, we could see that the circle centres from the top to the bottom become closer to the dotted line, which indicated that the centre offsets decreased when the speed increased. We found that the centre offset of the toe trajectories from walking at 0.8–1.2 NC changed linearly with cadence (Fig. 5b).

The estimated linear regression is:

$$\text{Offset} = 4.95 \times \text{Speed} + 9.66, \quad R = 0.996 \tag{9}$$

In the above equation, offset refers the centre offset, which is the value (in %) normalised by leg length, while speed is the ratio of the investigated walking cadence to the normal cadence.

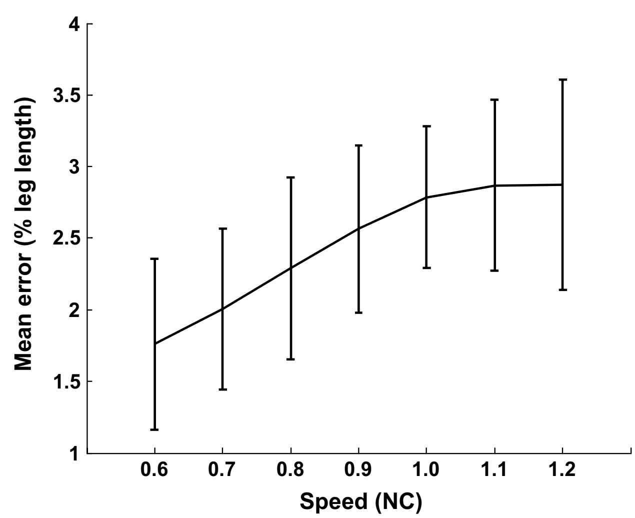

Fig. 4 Mean error between the best-fit circle and the relative toe trajectories from all subjects walking at seven speeds

Subject S6 had forward and backward angles of 18° and 15° during walking at her NC (Fig. 2b). The forward and backward toe angles for all subjects walking at seven speeds are presented in Fig. 5c, d. Both angles changed linearly with the walking cadence. The approximation functions are as follows:

$$\theta_1 = 11.134 \times \text{Speed} + 16.8, \quad R = 0.992 \tag{10}$$

$$\theta_2 = 13.83 \times \text{Speed} + 11.1, \quad R = 0.995 \tag{11}$$

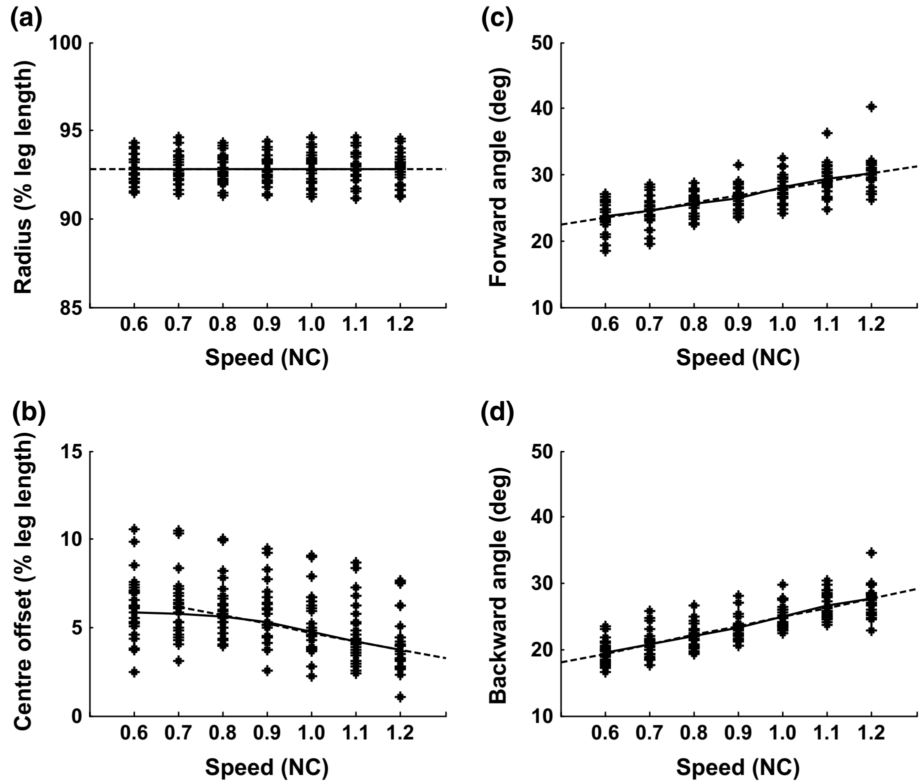

Fig. 5 Parameters of the best-fit circle curve for the relative toe trajectory from all subjects walking at seven speeds and their fitted lines. *Stars* are the mean value for each individual walking at each speed. The *solid lines* connect the mean values for all subjects walking at seven speeds, while the *dashed lines* are the values obtained from the linear functions. **a** The radius of the best-fit circle; **b** the mean centre offset of the best-fit circle (the *dashed line* shown in this subfigure was obtained from the mean value during walking at 0.8–1.2 NC); **c** the forward angle; **d** the backward angle

In the above equations, θ_1 and θ_2 refer to the angles in degree, while speed is the ratio of the investigated walking cadence to the normal cadence.

4 Discussion

This paper describes a substantial further development of our previous work [6], which provided initial pilot data on the feasibility of using a circle to approximate toe trajectories relative to the hip. By collecting gait data from 24 subjects walking at various speeds, this work aimed to validate the circle-fit approximation of the relative toe trajectory and to investigate linear regression models for describing the toe movements during normal gait.

Investigation of around 500 trials of gait data demonstrated that the toe trajectory relative to the hip had an inherently curved shape and could be generally fit by part of a circle with good accuracy. It should be noted that in gait analysis experiments the movement of the second metatarsal joint rather than the hallux is often recorded to represent the toe trajectory [9]. Therefore, the toe, as investigated in this study, does not involve the phalanges. The toe moved in a complicated path relative to the ground, while the toe trajectory relative to the hip had similarly curved stance and swing phases. During the stance phase, the foot was on the ground, while the hip was pivoted on the toe to move forward like an inverted pendulum [11]. It is reasonable that the toe trajectories relative to the hip during the stance phase are part of a circle. In contrast, during the swing phase, the toe moved forward in an irregular path, with the vertical amplitude ranging between 2 and 7 % of leg length above the ground. The hip joint oscillated vertically with an amplitude of 4 % of leg length relative to the ground. It was expected that the distance between the hip and toe trajectory would change little, which supports the use of a circle to approximate the toe trajectory relative to the hip. We found that the moving curves of the hip and the toe were similar in all subjects. Thus, the toe trajectory relative to the hip was generally curved, irrespective of height, age and walking speed. The best-fit circle algorithms yielded the fit circles for the curved toe trajectory. The circle approximated the relative toe trajectory with a negligible mean error, which validates the circle-fit approximation of the toe trajectory relative to the hip.

Based on the circle approximation method, our study explored the functions of circle parameters to model the toe trajectory. The toe trajectory could be described using a circle which was defined by the radius, centre offset and the curve range. Each subject had a fixed leg length; therefore, we expected the observed constant radius (about 93 % of the leg length) of the best-fit circles for the relative toe trajectories, regardless of walking speed. In contrast, the centre offset increased when the cadence reduced, which was consistent with the observation from our previous work [6]. When the walking speed reduced, the backward angle reduced faster than the forward angle. Therefore, the circle centre, which was generally located over the middle of the toe trajectory, moved further from the hip joint centre. Furthermore, the offsets, after being normalised by leg length, were found to reduce linearly with the cadence, when walking at 0.8–1.2 NC. The step length, which was represented by the curve range in this study, changed linearly with walking cadence. Summarising the walking data from the all subjects yielded the linear regression functions of the circle offsets and curve ranges, in relation to walking cadence. However, walking has physical restrictions. For example, the forward and backward angles should not be larger than 90°, and the centre of the best-fit circle should be located horizontally within the step length. It was expected that in these functions of the circle offset and curve ranges, the walking cadence should be within a certain range. Our study showed that the linear functions of the forward and backward angles were applicable for walking at speeds ranging from 0.6 to 1.2 NC, while that of the centre offset was found to only be applicable for speeds between 0.8 and 1.2 NC. The mean speed during walking at 0.6 NC was observed to be only 40 % of the speed during walking at 1.0 NC, which was too slow for a proper gait. The speed range for 0.8–1.2 NC was 0.58–1.87 m/s (Table 1), which covers the walking speeds we normally adopt in our daily life [21]. The functions for producing the toe trajectory at a speed lower than 0.8 NC or higher than 1.2 NC require further investigation. Nevertheless, the functions obtained in this study were able to produce the general toe trajectory based on leg length and walking speed when the walking cadence was between 0.8 and 1.2 NC.

The usage of a circle to approximate the toe trajectory relative to the hip has potential application for the design of gait robotic systems. It was anticipated that the toe trajectories relative to the ground are influenced by many factors including anthropometric features and individual gait control strategies [15]. However, we found that the toe trajectories relative to the hip for all the subjects had a limited deviation. The consistency of the curved feature of the toe trajectory relative to the hip supports the adoption of the end-effector strategy in gait orthosis design. Our study suggests that we could use a single bar to produce the toe trajectory, where the bar length is equal to the circle radius, the pivot centre corresponds to the circle centre, and the range of motion of the bar corresponds to the length of the toe trajectory, i.e. the summation of forward and backward angles. Based on the observation that the centre offset moved further from the hip joint centre when the walking speed reduced, the pivot of the bar should be adjusted according to the speed: if we generate walking at a higher speed, the pivot should be close to the hip joint centre. In contrast, if we simulate slower walking, the pivot should be adjusted to be further from the hip joint centre. Using the regression functions obtained, we determined the bar setup that can produce the toe movement for a general population walking at a large range of cadences. The inherent curved shape of the toe trajectory provides an efficient and reliable way to reproduce its movement path similar to normal gait.

5 Conclusions

By investigating the shape of the toe trajectories from 24 able-bodied subjects walking at seven speeds, we conclude that the toe trajectory relative to the hip joint has an inherently curved shape and can be well fit by part of a circle. The circle radius, the centre offset and the curve range of the circle curves approximating the toe trajectories from various speeds were determined through linear functions. These linear relationships could be used to systematically estimate the toe trajectories from the leg length and speed measurements. This increased understanding of the circle approximation of toe trajectories provides a potential design approach for gait orthosis robotics.

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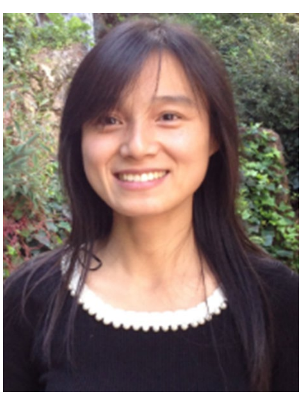

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