Trajectory Generation for Hip Rehabilitation Exoskeleton Using Trajectory Morphing Method

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Abstract—**A walking rehabilitation exoskeleton robot is meant for patients who are having walking difficulty, while endure their walking therapy by wearing it on his lower body. If that kind of patient are using predefined normal gait directly to the body, they may feel discomfort and lead to a painful therapy. It can endanger the patients' limb during the therapy session. Due to that painful reason, the patient would feel discouraged and demotivated to continue the therapy. This paper presents the usage of hip trajectory generation as reference input to the rehabilitation exoskeleton. The patient with current trajectory is used and morphed to target the normal walking trajectory. This generates a sequence of regular changing hip trajectories. The result is that a successive trajectory can be used as reference input while planning a hip rehabilitation therapy session for a specific period.**

Keywords—Trajectory generation; trajectory morphing; Hip joint trajectory

I. INTRODUCTION

Trajectory generation is a process of producing a trajectory profile to be used as reference input. A rehabilitation exoskeleton [1] robot joints will follow the reference input by following the trajectory tracking strategy [2]. The exoskeleton joints resemble human lower body joints consisting of hip, knee and ankle joints. The joints trajectories must be made available to control the exoskeleton to produce human like movement based on normal human gait for patient using it to do the walking therapy over conventional therapy [3] .

Some researches have generated [4] or planned the trajectories [5] based on recorded human gait [6], sensed human gait [7], polynomial based [8] and online/offline learning [9]. However, in these researches, no consideration has been made on the original state of the patient walking profile to be included in the trajectory generation. Abnormal gait data may be in form of paraplegic, weak leg or paresis data and compared with normal gait data obtained from normative data for normal walking.

Consequently, there is a large gap between the patient with current abnormal walking trajectory and the intended normal walking trajectory. To achieve the target, patient may undergo a painful and stressful therapy sessions as the patient who are donning the rehabilitation exoskeleton will need to firmly follow its movement. This would be a problem if the undergoing therapy between two consecutive therapy sessions has no gradual shift for the abnormal walking trajectory or a large trajectory jump to achieve a normal walking trajectory. The exoskeletons' donned will force the patient to follow the new input trajectory steeply though there is big difference between last trajectory used.

The exoskeleton can be used in therapy for the rehabilitation of hip joint [10], [11]. In this

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hip rehabilitation therapy, the current state of a patient hip trajectory is taken and used when the patient was the first timer for therapy session. The mean of a normative hip trajectory from a normal population is taken as reference and compared with the specific current trajectory of the elderly or patients with hip problems.

The normative hip trajectory is normally consists of mean and the standard deviation of hip trajectory is taken from a population of healthy normal walking person. The reference trajectory may not differ much from a person to another one but the abnormal trajectory is for a specific person. Focusing on the hip joint, a series of hip trajectories that gradually shift abnormal hip trajectory towards the target normal hip trajectory is generated.

II. METHODOLOGY

The trajectory to be generated is the hip position angle trajectory through a morphing method from a trajectory to another trajectory. Trajectory morphing has been used in other area like producing target trajectory for puppet from a given source [12] and producing trajectory for non-linear cart and pendulum system [13]. Although the method is also used in linear image morphing [14], the same technique can be applied for shape morphing; and in this case is hip trajectory shape. The trajectory morphing for obtaining hip angle trajectory is done by the mapping of the abnormal hip trajectory onto normal hip trajectory; then, the abnormal trajectory has changed its shape to resemble the normal trajectory. In between, the two initial trajectories, a series of trajectories is generated.

A. Trajectory data preparation

For this trajectory generation, the normal trajectory data is taken from the mean of a normative data [15] and the abnormal trajectory data is taken from the actual patient data [16] in one gait cycle (see Appendix). The normal trajectory data consists of 101 data while the abnormal trajectory data consists of 51 data. The abnormal trajectory is a trajectory deviation from the normal trajectory. One gait cycle or 100% gait is taken from toe off to the next toe from a leg.

A stride time is defined as time taken in seconds to complete a gait cycle or a period taken over 100% gait. Both trajectories are modelled and approximated using quantic polynomial equations [17] as Equation (1) for normal trajectory (yn) and Equation (2) for abnormal trajectory (yan) where y itself denotes the hip joint angle and x denotes time.

$$y_n = 10^3\begin{pmatrix}-1.2820x^5 + 2.2247\,x^4 - 0.8060\,x^3\\ -\,0.1257x^2 - 0.0144x + 0.0334\end{pmatrix} \quad (1)$$

for $0.02 \le x \le 1$

$$y_{an} = \begin{pmatrix}-5.1326x^5 + 28.6548x^4 - 42.1360x^3\\ +14.1871x^2 - 22.0544x + 45.8206\end{pmatrix} \quad (2)$$

for $0.06 \le x \le 3$

The stride times for normal and abnormal are different although the gait cycle is always fixed. A gait cycle may have different stride time for different patient conditions. The stride time for a normal person is shorter than the stride time for abnormal person. Fig. 1 shows the plots of the normal (blue curve) and abnormal (red curve) hip trajectories plotted on the same graph based on the longer stride time. In the hip rehabilitation therapy, the shorter stride time is the target to achieve as in the normal hip trajectory. When plotted against time, it shows transition in stride time and range of motion (ROM) towards target while it also indicates the increasing of walking speed when the stride time decreases.

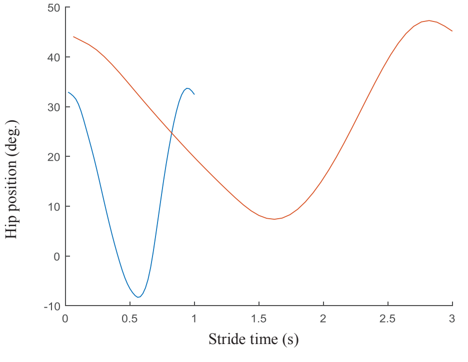

Fig. 1. Normal and abnormal hip trajectories plotted vs time.

In Fig. 2, while the graph shows the abnormal trajectory ROM intended to move towards the target normal trajectory ROM, it also indicates the abnormal trajectory to move downwards towards the targeted normal trajectory. The trajectories are based on numerical dataset consisting of hip joint angle versus time obtained from clinical gait analysis (CGA) data. Table 1 shows the hip joint position range, the range of motion (ROM) and the stride time for both profiles.

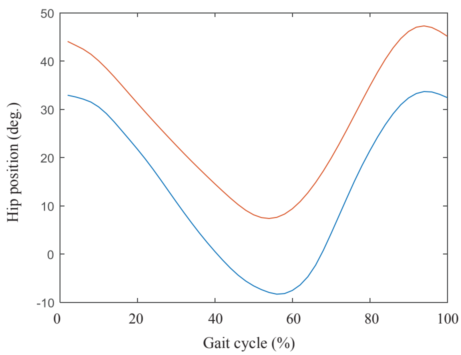

Fig. 2. Normal and abnormal hip trajectories plotted vs % gait.

TABLE I. PROPERTIES FOR BOTH PROFILES

Properties	Hip Joint Angle (deg.)	Range of Motion (ROM) (deg.)	Stride Time (s)
Abnormal	7.37 – 47.29	39.92	3.0
Normal	-8.31 – 33.69	42.00	1.1

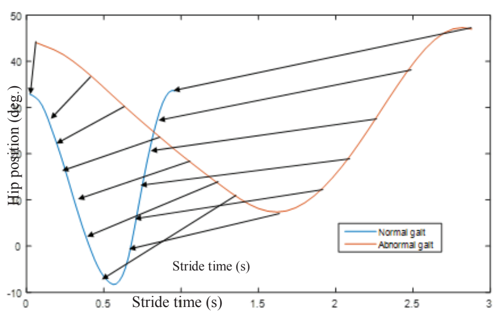

Fig. 3. Point-to-point mapping from abnormal to normal trajectory.

B. *Mapping of trajectory curves*

Due to different number of data points between both trajectories, interpolation is made on both trajectory curves. Interpolation is a method of constructing new data points within the range of the existing data points shown in the Appendix table. The new data points are constructed at a fixed interval. In this case, both trajectories in Fig. 3 are interpolated and divided into 50 points of fixed interval each. A point-to-point mapping of normal and abnormal joint trajectories is applied where point 1 on abnormal trajectory is mapped linearly onto point 1 on normal trajectory sequentially until point 50 along both trajectories as illustrated in the figure. Straight line is used for linear mapping because it is the shortest path to map between two points on both trajectories. As a result, there are 50 lines connecting each new point on normal trajectory to a new point on abnormal trajectory but in sequentially. Again, each line is interpolated within the range of the two new points to produce another 8 points that resulting for each line be divided into 10 points at equal interval starting from point 1 on abnormal trajectory sequentially to point 10 on normal trajectory.

C. *Generating the intermediate trajectories*

Each point 1 on all lines is connected from line 1 up to line 50 to form a curve. These are repeated in sequential order until reaches point 10 to form a sequence of eight trajectories as shown in Fig. 4 with each trajectory can be used at a time for a therapy session. The generated trajectories lie within the normal and abnormal trajectories. Hip trajectories have been produced for gradual hip rehabilitation therapy sessions would be moving from abnormal to normal trajectory. The overall concept is illustrated in Fig. 5.

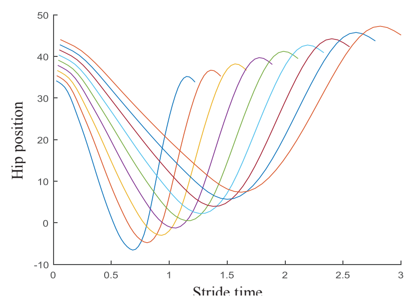

Fig. 4. Generated series of trajectories between normal and abnormal trajectories plotted vs time.

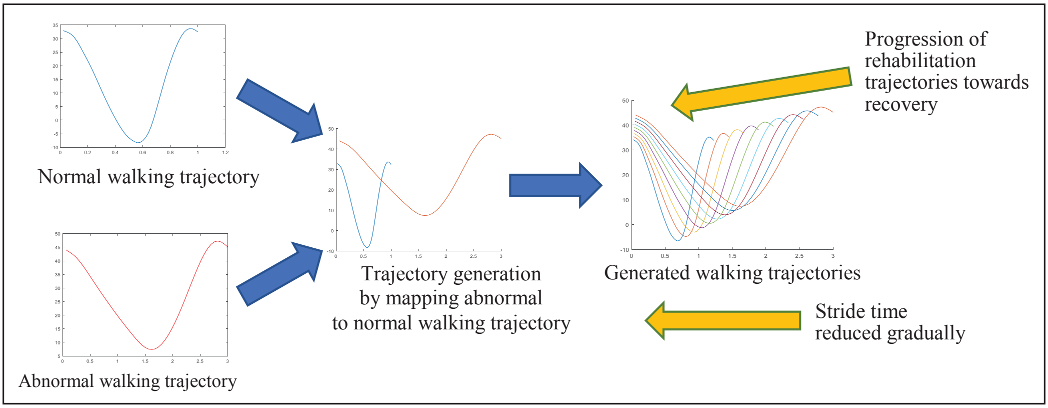

Fig. 5. Overall trajectory morphing concept.

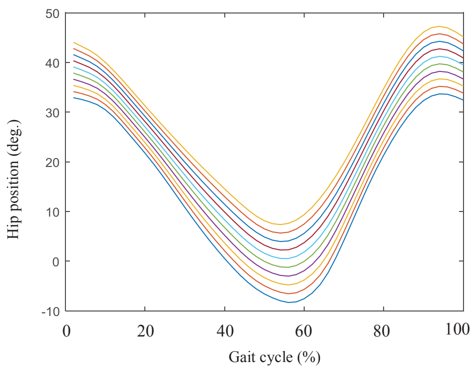

Fig. 6. Generated series of trajectories between normal and abnormal trajectories plotted vs % gait.

While Fig. 4 shows the generated trajectories that plotted over the stride time, Fig. 6 shows the same trajectories when plotted over a 100% gait cycle. The top curve is the abnormal trajectory while the bottom curve is the target normal trajectory. It shows the path for the trajectory transition downwards towards recovery in the therapy sessions.

D. Trajectory in acceptable band

For the purpose of reviewing the recovery process, Fig.7 shows the red trajectory for the abnormal one and blue trajectory for the trajectory near to the normal trajectory. The normal trajectory is the bottom trajectory shown in previous graphs, but this time what is shown as normative trajectory with mean indicated by the bold curve and its standard deviations in forming the upper and lower limit. The area between the upper and lower limit gives the acceptable band. Once a trajectory falls within the acceptable band, it can be deduced that the progress of hip recovery has taken place. In Fig. 7, part of blue trajectory would falls in an acceptable band while other parts fall beyond the band; but it show that recovery is in progress as well. Final trajectory that had been used for hip rehabilitation therapy must have most progress to fall within the acceptable band.

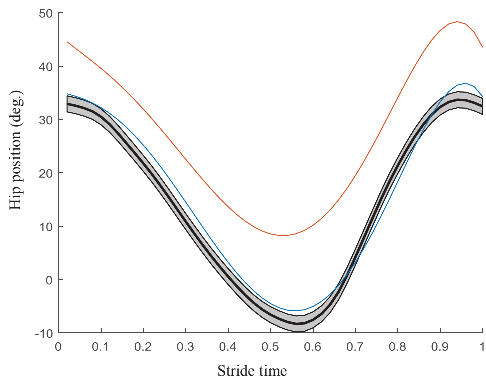

Fig. 7. Normative data plot with mean and standard deviation is forming the acceptable band.

III. RESULTS AND DISCUSSION

The generated trajectories are gradually moved or shifted successively from the abnormal trajectory towards normal trajectory thus reducing the stride time too. The generated trajectories are successive with each new trajectory continues to shift a little each time a new trajectory is produced. The new trajectories continue to generate until the last generated trajectory is getting like and resemble the target trajectory. In this case, there are eight new trajectories being generated including the original trajectory and the target trajectory. Stride time from the original trajectory has been reduced gradually from 3s to 1s in ten successive trajectories.

If the normal trajectory is plotted in the form of normative data with ± 1σ, the range between mean + 1σ and mean - 1σ is considered as acceptable range for hip recovery. That means that any generated trajectories that fall within the range are considered acceptable. The range gives the acceptable band and can be used for further therapy sessions to reach hip recovery. The trajectories of the acceptable band or in other words the recovery band is used as indicator that hip trajectories used within that range can be used as reference inputs to hip rehabilitation exoskeleton to help patients undergoing the therapy to regain their hip joint abilities to move as a normal person should.

CONCLUSION

The generated successive trajectories can be used in planning a hip rehabilitation therapy number of sessions within a specified duration. In each session one trajectory can be selected for usage as a reference input to hip rehabilitation exoskeleton and in guiding the patient who are wearing the exoskeleton. In subsequent therapy session, the selected trajectory is changed to a gradual match the normal trajectory throughout the rehabilitation course. Generating trajectories by taking the abnormal trajectory and normal trajectory into consideration can be judged more effective than applying trajectory by the therapist instinct through observation in a therapy session.

This method can help reduces the burden of the therapy sessions for the patient while helping the therapist to plan for the hip rehabilitation therapy process effectively. Following this, a patient recovery plan can be produced and the expected time or duration for the patient hip recovery attainment can be predicted. The patient can experience painless rehabilitation therapy session and fast recovery with planned rehabilitation course as the patient would undergone each therapy session according to his recovery performance.

APPENDIX

Table of data for normal and abnormal hip angle for one gait cycle equivalent to one stride.

Normal			Abnormal		
% cycle	Time	Angle	% cycle	Time	Angle
0	0.00	33.00	0	0.00	45.00
1	0.01	33.00	2	0.06	44.07
2	0.02	32.90	4	0.12	43.28
3	0.03	32.73	6	0.18	42.48
4	0.04	32.49	8	0.24	41.41
5	0.06	32.24	10	0.30	40.05
6	0.07	31.98	12	0.36	38.48
7	0.08	31.64	14	0.42	36.76
8	0.09	31.17	16	0.48	34.95
9	0.10	30.56	18	0.54	33.10
10	0.11	29.86	20	0.60	31.27
11	0.12	29.04	22	0.66	29.47
12	0.13	28.13	24	0.72	27.69
13	0.14	27.14	26	0.78	25.95
14	0.15	26.11	28	0.84	24.23
15	0.17	25.07	30	0.90	22.53
16	0.18	24.04	32	0.96	20.86
17	0.19	23.00	34	1.02	19.23
18	0.20	21.94	36	1.08	17.65
19	0.21	20.86	38	1.14	16.09
20	0.22	19.75	40	1.20	14.56
21	0.23	18.59	42	1.26	13.06
22	0.24	17.41	44	1.32	11.61
23	0.25	16.19	46	1.38	10.25
24	0.26	14.95	48	1.44	9.06
25	0.28	13.69	50	1.50	8.14
26	0.29	12.43	52	1.56	7.56
27	0.30	11.18	54	1.62	7.37
28	0.31	9.94	56	1.68	7.61
29	0.32	8.72	58	1.74	8.29
30	0.33	7.53	60	1.80	9.38
31	0.34	6.35	62	1.86	10.87
32	0.35	5.19	64	1.92	12.69
33	0.36	4.07	66	1.98	14.82
34	0.37	2.98	68	2.04	17.22
35	0.39	1.93	70	2.10	19.85
36	0.40	0.90	72	2.16	22.69
37	0.41	-0.09	74	2.22	25.66
38	0.42	-1.06	76	2.28	28.72
39	0.43	-2.00	78	2.34	31.79
40	0.44	-2.90	80	2.40	34.81
41	0.45	-3.73	82	2.46	37.70
42	0.46	-4.51	84	2.52	40.37
43	0.47	-5.21	86	2.58	42.72
44	0.48	-5.83	88	2.64	44.67
45	0.50	-6.37	90	2.70	46.13
46	0.51	-6.85	92	2.76	47.02
47	0.52	-7.26	94	2.82	47.29

Normal			Abnormal		
% cycle	Time	Angle	% cycle	Time	Angle
48	0.53	-7.62	96	2.88	46.97
49	0.54	-7.94	98	2.94	46.17
50	0.55	-8.19	100	3.00	45.15
51	0.56	-8.32			
52	0.57	-8.32			
53	0.58	-8.14			
54	0.59	-7.80			
55	0.61	-7.33			
56	0.62	-6.70			
57	0.63	-5.91			
58	0.64	-4.92			
59	0.65	-3.73			
60	0.66	-2.31			
61	0.67	-0.69			
62	0.68	1.09			
63	0.69	3.00			
64	0.70	4.97			
65	0.72	6.95			
66	0.73	8.95			
67	0.74	10.95			
68	0.75	12.93			
69	0.76	14.88			
70	0.77	16.75			
71	0.78	18.53			
72	0.79	20.22			
73	0.80	21.85			
74	0.81	23.43			
75	0.83	24.94			
76	0.84	26.34			
77	0.85	27.65			
78	0.86	28.86			
79	0.87	29.97			
80	0.88	30.95			
81	0.89	31.79			
82	0.90	32.48			
83	0.91	33.02			
84	0.92	33.41			
85	0.94	33.65			
86	0.95	33.73			
87	0.96	33.66			
88	0.97	33.45			
89	0.98	33.15			
90	0.99	32.78			
91	1.00	32.39			
92	1.01	32.03			
93	1.02	31.73			
94	1.03	31.53			
95	1.05	31.44			
96	1.06	31.45			
97	1.07	31.55			
98	1.08	31.71			
99	1.09	31.89			
100	1.10	32.03			

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