User-friendly hip and knee trajectory generation of healthy gait patterns for robotic rehabilitation systems

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Abstract

This paper presents a novel approach for hip and knee flexion/extension trajectory generation to be used in robotic-based gait rehabilitation systems. The proposed method receives a set of minimum and maximum flexion/extension points for each joint curve, automatically calculates a set of additional curve-shaping knots and finally generates healthy joint patterns. Two offline algorithms and their results are presented: one to obtain the way to calculate the time and angle parameters of the shaping knots, and another one to show the adaptation capabilities of the method which allows the modification of curves towards more desired patterns.

1 Introduction

For over a decade robotic rehabilitation systems have been trying to break the paradigm of manual gait rehabilitation offering several devices able to assist the therapists during the therapy sessions. The main aim of these systems is to give tireless and precise assistance to the patient in order to improve and/or regain his/her lower limb motoric functions. To accomplish this, reference gait trajectories in either joint or world space are introduced to enable the device to assist the patient towards the achievement of non-pathological gait patterns. Therefore, the generation of these trajectories is of great importance for the therapy.

Not many publications address in detail the issue of trajectory generation and manipulation for robotic gait rehabilitation systems. Some of the ones addressing this topic are presented below. The Lokomat system, implements position control to track fixed angular trajectories of knee and hip joints based on recordings of healthy gait patterns. Not much information is given about the selection of these reference trajectories, but it is known that it is made based on the height and range of motion at the joints [1]. Researchers using Lokomat have proposed different trajectory adaptation algorithms in the search of 'patient-cooperative' therapy [2], which modifies the joint curves influenced by the patience active participation. The NaTUre-Gaits system incorporates the GaitGen [3] [4] [5] [6] [7]. Several approaches are made by this research group, which include the combination of user input of patients' anthropometric and gait parameters, the implementation of different artificial neural networks, and the usage of curve fitting algorithms such as cubic splines and Fourier series, all the previous in the search of patient-specific gait patterns generation. The LOPES system [8] group has also published some strategies for trajectory generation, including [9] where reference trajectories for hip ab-/adduction, and hip and knee flexion/extension are obtained based on measurements done to unimpaired subjects, predicting some key curve parameters and interpolating them into the final joint curves via B-splines. In [10], a special Fourier-based interpolation method is implemented to generate cyclic foot trajectories for the HapticWalker. In [11], a pattern adaptation approach is shown for the ALEX system [12], where the patient's pre-training pattern is initially gotten and then modified towards a healthy pattern depending on the patient's progress. In [13], a model-based adaptation tool is offered to be used in the LERE system, focused on deriving adaptive joint trajectories by minimizing the active torque exerted by the patient, with the help of the inverse dynamic model, a fuzzy adaptation algorithm, and a trajectory generator.

From most of the mentioned studies it can be seen that the freedom given by the actual systems to the doctors and therapists to adapt the gait patterns to fit a specific patient's capabilities is very constrained, limited to set just very general parameters such as cadence and walking speed. Most of the trajectory-related handling is non-transparent and inaccessible to the users. The objective of this paper is to give users the opportunity to automatically generate hip and knee angular displacement curves of healthy gait patterns and adapt them through an easy graphical manipulation of the local minimum and maximum angular positions for hip and knee flexion/extension. This trajectory generator has been developed within the project MOPASS, a new mobile gait rehabilitation system comprising an orthosis with active hip and knee joints (sagittal plane) and a motorized platform.

2 Methods

Initially a study on curve fitting algorithms was conducted to find a suitable method to generate hip and knee trajectories from the placement of curve shaping knots. Six different interpolation methods were studied, shown in Table I. Specifically, four key characteristics were analysed: degree of continuity, locality, piecewise monotonicity and polynomial degree. Given the characteristics of the application, a minimum degree of continuity of 2 was selected (continuous in position, velocity and acceleration). Plus, piecewise monotonicity was compulsory to ensure the minimum and maximum points in the curves. On the other hand, locality was preferable, but not a must, same as the preference for lower polynomial degrees for lower complexity. Finally, BVSIS (Boundary-Valued Shape-preserving Interpolating Spline) was selected as interpolation method. BVSIS was later used to develop an algorithm to find the way to automatically place curve-shaping knots (additional to the local minimums and maximums) in order to create healthy gait patterns. For this, twenty healthy curves (for each joint) were extracted from study results of several publications. Since the original measurements were not available, these curves were gotten from the figures of the publications and manually sampled every 1% of the gait cycle period. The curves include gait trajectories of adult subjects walking at normal, fast and slow speed, and of children walking at normal speed. Fifteen of the 20 reference curves where randomly selected to feed the knot placement algorithm, while the remaining 5 where used to test the results.

The developed algorithm aims for a minimization of the sum of normalized position squared errors over all the samples of all the training reference curves, and delivers sets of multipliers used to calculate normalized values of time and angular displacement for the additional curve-shaping knots. These values are relative to the minimum and maximum points (specific for each reference curve) surrounding the additional knot. The algorithm goes over each gap between a minimum and a maximum point of the curve, calculating the error square over the 100 samples of all the curves while changing the time and angular values of the additional knot(s) located in the current gap[1]. A simplified state diagram of the algorithm can be seen in Fig. 1, while an example (taken from the test set) of the hip and knee curves generated with the results yielded by the algorithm is shown in Fig. 2. As it can be seen, each joint curve has 2 minimum and 2 maximum knots, giving 4 gaps per curve. The hip curve has 2 gaps holding 2 shaping knots each, whereas in the knee curve the 4 gaps hold shaping knots: the first 2 hold one knot each and the last two hold two knots each. This selection of knots was made after conducting preliminary studies with different number of knots. This leads to a total number of knots of 8 and 10 for the hip and knee curves, respectively, needed to generate the trajectory.

Additionally, a second algorithm was developed to show how close a generated trajectory can fit any of the reference trajectories just by slightly changing the time parameters of the curve-shaping knots.

3 Results

The first algorithm was run three times for each joint[2]. The resulting set of knots given by the first algorithm yielded a normalized position error (per sample) of 0.029 and 0.03 for the training set and the test set, respectively, for the hip joint, and 0.023 and 0.02 for the knee joint. The mean squared errors, standard deviations and mean absolute errors of the obtained results, for the train and test sets can be seen in Table II, as well as the overall results for the complete set of 20 reference curves. This results show that with the given method it is possible to reconstruct joint trajectories just with a set of 4 min/max knots per curve. Nevertheless, it is important to point out that during the study hip curves with only one pair of min/max points were found. In these cases it is possible to include an extra pair of knots (e.g. where the curve shows higher inflexion) around or aside the maximum point, as shown in Fig. 4. This will not affect the interpolation algorithm and will ensure that the generated curve will pass through these points.

Additionally, the second algorithm showed that, by moving the (relative) time parameters of the shaping knots an average of 2.2% of the time between the adjacent minimum and maximum points, the mean normalized absolute position error can be decreased to 0.0096 and 0.0066 for hip and knee curves, respectively, calculating over all the 20 reference curves. This indicates that it is possible to manually modify the generated curve towards a more desired one (in this case, to match almost perfectly the reference curves) just by minimally adjusting the time parameter of one or more of the shaping knots. An example is shown in Fig. 3.

4 Conclusion

The results showed that it is possible to generate knee and hip trajectories for healthy gait patterns by just selecting a suitable set of (local) minimum and maximum flexion/extension positions of the joints. Additionally, this method gives the users the chance to manipulate directly and in an intuitive way the joint curves, allowing them to adapt the curves easily towards more desirable ones. In the same way, it gives the chance to generate more personalized trajectories dependent on the specific (dis-) abilities of a patient and his/her performance, allowing even the generation of gait patterns that may not be considered healthy, but are more suitable for a specific patient. Finally, this new approach opens new possibilities to develop novel strategies for 'assist-as-needed' and 'patient-influenced' robotic-based therapy different from the present ones. Intended

[1] Some restrictions were applied, e.g. that the minimum relative distance in time between two knots is 20%

[2] No significant changes were reported between the results of the 2^{nd} and 3^{rd} runs, indicating that the algorithm had converged to a desired result.

further work will be focused on the automatic selection of the min/max points depending on desired gait features and patient's characteristics, for what a correlation study with different subjects must be held.

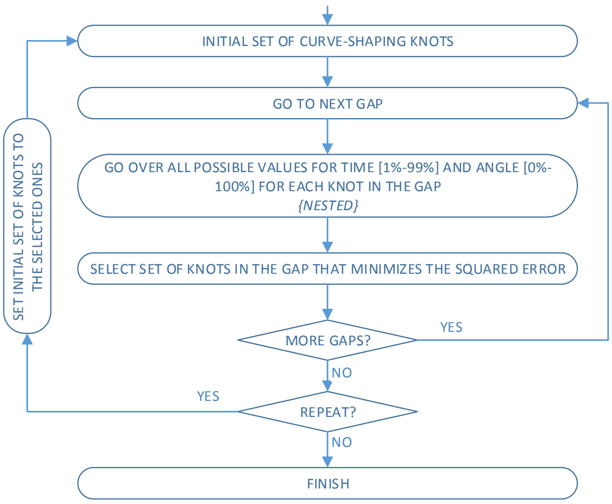

Fig. 1. State diagram of the error minimization algorithm for shaping-knot modification

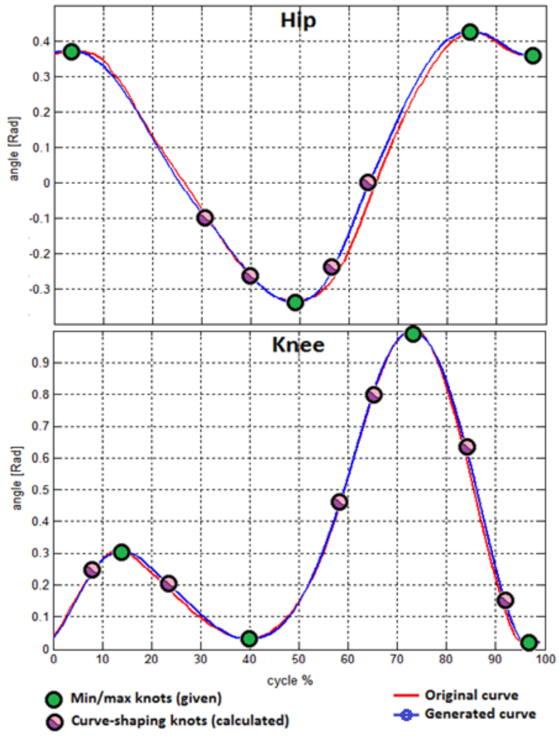

Fig. 2. Example of hip and knee generated curves

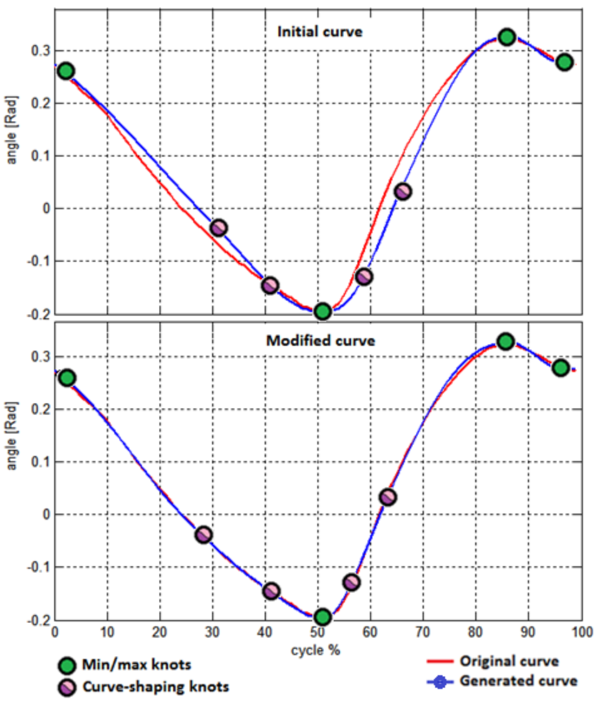

Fig. 3. Example of adjustment of a curve via its time parameters

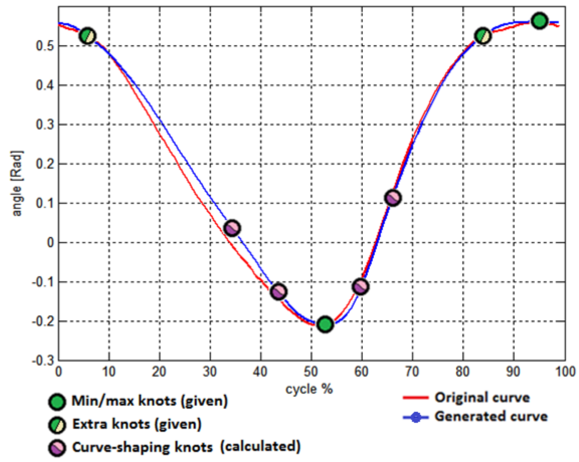

Fig. 4. Example of hip curve with one pair of min/max knots

Method	Continuity degree	Locality	Piecewise Monotonicity	Polynomial Degree
(MATLAB) Spline	C^2	No	No	3th
PCHIP [14]	C^1	Yes	Yes	3th
PQHI [15]	C^2	Yes	Yes	5th
BVSIS [16]	C^2	Yes	Yes	6th
SDDEEL [17]	C^2(if possible) Minimum C^1	No	Yes	3th
Periodic spline [18]	C^2	No	No	3th

Table I: Main features of the studied interpolation methods

		Training	Test	ALL
HIP	**MNSE**	0,0008	0,0009	0,0008
	SD	0,0013	0,0007	0,0021
	MNAE	0.0283	0.03	0.0283
KNEE	**MNSE**	0,0005	0,0004	0,0005
	SD	0,0015	0,0008	0,0013
	MNAE	0.0224	0.02	0.0224

Table II: Results of the knot-placement algorithm. MNSE: Mean Normalized Squared Error (per sample). SD: Standard Deviation. MNAE: Mean Normalized Absolute Error (per sample)

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