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Dynamic Behavior of Human Locomotion during Ascending Stairs

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***Abstract*— Human gait locomotion has been studied a lot since the human balance during daily routine is of interests of scientists and has the rehabilitation and robotic applications. In this study the dynamic behavior of the human gait during stair ascent has been studied and an innovation model has been developed based on holistic approach using Poincare's method and it will describe the leg joints coordination and interactions. Five healthy subjects were tested. Phase plane of lower extremities joints were constructed for sagittal plane. The desired dynamic was designed based on the intersection of Poincare sections and joint's trajectories. The results indicate that the system has the limit cycle dynamic and it shows a stable behavior.**

I. Introduction

Going up and down stairs is a routine activity of daily life. From a mechanical perspective, it is quite different from level walking. The differences are reflected by changes in the ranges in the phasic muscle activities, in the maximum joint forces and moments. For stair climbing, a cycle contains the movement of the body from one step up/down to the next. A cycle starts with both feet on a stair and then one foot is lifted or pulled off the surface of the step. During initial ascent phase, limb is lifted from the stair. Placing the foot securely on the next step will end this initial phase. At this point in the cycle, pull up begins. It constitutes the limb's forceful extension on the next step to raise the body from the step. The phase will be ended when the foot on the original step contacts the next step [1, 4].

Most of the researchers who work in robotics, confirm that biology and self-organization ideas could have a huge impact on the autonomous robots' designs. Human balance, stable standing and unleveled walking is of critical importance to human motor control during standing and walking in daily life [3].Although many papers have been published on the planning and executing walking gaits for humanoid robots, most of them were concerned with walking on level ground[5], [6], [7], [8].[9-11].

Understanding the lower extremities mechanism during stair ascent is an important step toward identifying the system that it may help to greater knowledge of the pathogenesis disorders. It will also be useful for joint replacement prosthesis design and robotic design. In this study the human dynamic system is characterized as a holistic model and step is synthesized as a desired trajectory through state space that continuously enforced by applying stabilizing trajectory control. This study proposes the new approach with fewer artificial constraints and more robust stepping motion which is based on non-linear analysis.

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II. Methdos

A. Human Locomotion data

This study is performed on the Mocap database HDM05 available at [25] which is a system based on an optical marker-based technology. This system provides detailed and clean data. The subjects are worn a suit which is equipped by 40-50 retro reflective markers. High-resolution cameras record the markers with the frame rate of 120 Hz. The dataset consist of 5 young normal subjects. The database consists mocap data in ASF/AMC and C3D format. A Matlab parser has been used to read the data. The data consist of a few steps level walking and then climbing stairs on a 3 step stair case and then again a few steps level waling. All the level walking and stair ascending movements are marked in the MOKKA (motion kinematic and kinetic analyzer) software.

B. Phase Plane

Typical data has the locations of each segment endpoints. So to calculate the relative angles between the longitudinal axes of two adjacent segments are used and hip, knee and ankle angles are calculated based on the law of Cosines.

A phase plane will be formed using calculated three joints angles. Phase plane is a form of state space where the position of joints or segments are plotted relative to each other and has the capability to show the relation of angle dynamics in time. The phase plane representation is a first and critical step in the quantification of coordination nonlinear systems such as human movements [14-16].

So, we would have a 3D phase plane, which enable us to investigate the system dynamics (shown in figure 1). It can be seen that in the phase plane of two or more dimensions, new type of behavior has been arisen which is a motion on a limit cycle. Limit cycle is defined here, as a nominally periodic sequence of steps, which is stable as a whole, but not stable at every instant time. On the other hand, the intended motion (stepping here without any disturbance ideally) is a series of closed trajectory repetition in state space (limit cycle). This trajectory may not be stable locally at every time instants. In this method, there is no need making all points on the trajectory, in state space to be attracted to their local neighborhoods. The motion, as a whole is stable since neighboring trajectories eventually approach the nominal trajectory[13].

C. Poincare Map

We use Poincare map to identify the dynamic equilibrium. Poincare (1899) proposed the idea of reducing the continuous time system study to study an associated discreet system[15]. In order to describe it quantitatively, the Poincare map function has to be used. The essential idea is that given a point X_1, where the trajectory crosses the Poincare plane, we can in principle determine the next crossing point X_2 by integrating the time-evolution equations describing the system. So, there must be some mathematical function, call it F, that $X_2=F(X_1)$. In general, we may write

$$X_{n+1} = F(X_n) \tag{1}$$

Analyzing the nature of the function F and its derivatives, gives us the nature of the limit cycle. Now the function F can take the form:

$$x_1^{n+1}= F_1(x_1^{(n)}, x_2^{(n)})$$

$$x_2^{n+1}= F_2(x_1^{(n)}, x_2^{(n)}) \tag{2}$$

The parenthetical superscript indicates the crossing point number.

The stability of these fixed points is determined by finding the characteristic values of the associated Jacobian matrix of derivatives. It is worth mentioning that finding the F function may be impossible in actual practice and in most applications a good estimate of it would be fine[12].

When using the nonlinear maps for measuring and processing the signals, simplicity and felicity of the system is more important thing. If complex calculations needed to imitate the iteration map, such model is applicable only for simulation studies rather than practical ones[21,22]. So we considered the simple enough and efficient iteration map for our purpose. The iteration variable is interpreted as the measure of an angle that specifies where the trajectory is on a circle.

$$\theta_{n+1} = f(\theta_n) \tag{3}$$

This notation is motivated by consideration of Poincare sections of state space motion on a torus. If the state space variables are properly scaled, then the intersection points will lie on a circle in the Poincare plane. Of course, for models of many physical systems and for many models based on differential equations, the tours cross section will not be circular. Even in those cases, we can use an angle to specify where the trajectory lies on the cross section. For almost all of our discussion, the details of the shape of the torus cross section are not important, and we gain a great deal of simplicity by using a circular cross section[23].

Now, stepping up the stairs is a rhythmic behavior, so in this study the sine circle map would be used to identify the reference trajectories of the rhythmic stepping behavior. A sine circle map is proposed as a nonlinear map function that takes the specific form of sine function with the nonlinearity. The sufficiency of this map is that it explains all the periodic, quasi-periodic and chaos behaviors of the systems [19, 20, 22]. It has a specific form of sine function:

$$\theta_{n+1} = \theta_n + \Omega - \frac{K}{2\pi}\sin(2\pi\theta_n) \quad mod[1] \tag{4}$$

The parameter K>0 is the measure of the strength of the nonlinearity. Ω is a frequency ratio. Comparing with single parameter maps, circle map has two parameters, which exhibits richer dynamic characteristics[18].

In order to study the long-term behavior of the system, we can compute the winding number, which is the rotation number.

$$w = \lim_{n\to\infty} \frac{f^{(n)}(\theta_0) - \theta_0}{n} \tag{5}$$

If the winding number is equal to p/q, then after q iterations we will have a recurrence, hence the map is periodic. Irrational winding numbers are contributed to quasi-periodic system dynamic.

D. Floquet Matrix

In order to find the stability, the function f in Eq. 1 is linearized at its fixed point (S^*) with only small perturbations.

$$S^* = f(S^*)$$
$$[S_{k+1} - S^*] = J(S^*)[S_k - S^*] \tag{6}$$

It can be seen that small perturbations rates to either grow or decay are proportional to the magnitude of the eigenvalues of matrix J. Thus, the stability of limit cycle requires that the eigenvalues of matrix J be within a unit circle[23].Hurmuzlu was first to use these eigenvalues that are called Floquent multipliers to study walking stability [23].

III. RESULTS

A. System's dynamic

Figure 1 shows the phase plane of the ankle, knee and hip joints for one of subjects during stair ascent. In order to apply the Poincare section, the gait events have been determined using original data. Transition form stance to swing phase and pull up phase have been marked on the data and considered as stair ascent events.

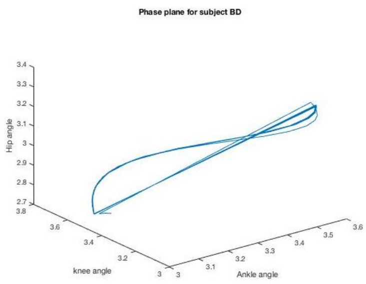

Figure1: 3D phase plane for subject BD

Figure 2 shows the Poincare section for subject BD that has been applied on the 3D phase plane.

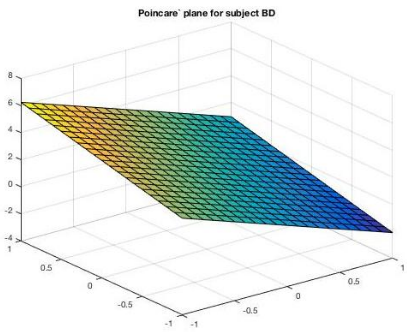

Figure 2: Poincare section

The sine circle map has been identified from the intersection of the data in phase space and Poincare section. Since each limit cycle has a 3D dimension, there are 3 values of K and Ω. Least square method has been used to estimate the map parameters. Table 1 shows the parameters values for all subjects.

Table 1: the identified parameters for desired map

Subjects	K	Ω
TR	0.0129 0.0780 0.1590	1.0000 0.9931 0.9741
MM	0.1178 0.0293 0.5266	0.9916 0.9954 0.9180
DG	0.0027 0.0032 0.0110	0.9991 0.9998 0.9980
BK	0.0520 0.1003 0.0064	0.9998 0.9993 0.9995
BD	0.0329 0.0410 0.1824	0.9971 0.9976 0.9719

In order to discuss the systems dynamic behavior, we need to recall the Arnold tongues, which are shown in Fig. 3 as regions that frequency locking occurs. Figure 3 shows a sketch of the 0:1, 1:2 and 1:1 frequency locking regions for the sine circle map along different values of K and Ω.

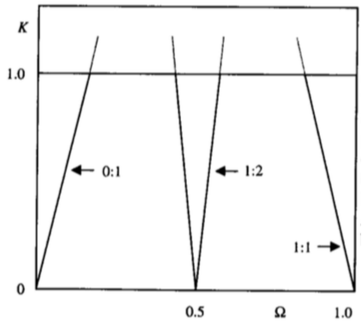

Figure 3: A sketch of 0:1, 1:1 and 1:2 frequency-locking regions for sine circle map [24].

As it can be seen from the table, all K values are between 0 and 1 and Ω values is close to 1, so 1:1 frequency-locking have been occurred for all of the subjects. In the other word, the motion is periodic and characterized by the winding number, W, which is rational corresponding to locked motion.

This confirms that the identified map is a limit cycle. Now we can study how trajectories approach or diverge from the Poincare intersection point of the limit cycle. In joint's basin of attraction, the trajectories are approach to the limit cycle from one point and diverge from another one. So it is referred that the identified limit cycle is a saddle cycle.

B. Stability

In order to characterize the stability of the system, the floquet matrix and multipliers have been computed. Table 2 shows the floquet multipliers for all subjects.

Table 2: Floquet multipliers along all subjects

Subject	Floquet Multipliers
TR	0.9963 + 0.0373i 0.9963 - 0.0373i
MM	0.9970 + 0.0530i 0.9970 - 0.0530i
DG	0.9884 + 0.0246i 0.9884 - 0.0246i
BK	0.9946 + 0.0305i 0.9946 - 0.0305i
BD	0.9775 + 0.1169i 0.9775 - 0.1169i

As you can see from table 2, all the multipliers all in the unique circle that confirms that the stability of the dynamic system.

IV. CONCLUSION

In this study human dynamic system during ascending stairs has been studied. As it explained before, we have designed and identified a desired dynamic for the system that is stable and it can be used as a control input of a biped robot. This findings confirms that the human dynamic system during ascending stairs is a stable nonlinear system and we have found a desired dynamic for the system that follow the human pattern very closely. Using this dynamic make the control much more efficient since there will be no need for the controller to follow the trajectory in every move. This desired dynamic may control the movement as a whole and keeping the trajectory close enough to the desired dynamic and it will be adequate to use as controller input.

In future study, the desired dynamic will be applied to a controller and its output will be compared by human's joint trajectories.

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