Isochron of human walking derived from the perturbation of floor

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Abstract: The rhythm of human walking is controlled for maintaining the stability. The stable motion composes limit cycle and the stabilization property is determined by the phase condition neighbor to the limit cycle described as isochron. This paper draws the isochron by analyzing the stabilization process after frontal perturbation. The isochron contained discontinuous flow around the hopping phase, considered to reflect the tuning of the phase control at hopping.

Keywords: Human walking, Isochron, Limit cycle.

1. INTRODUCTION

Walking is a cyclic motion actuated by the rhythm generated by the central pattern generator. The rhythm attracts the walking motion into stable cycle, which enables the walking with limited feedback control. Animals are considered to improve the stability by controlling the rhythm itself, such as resetting the rhythm by the timing of hopping and landing [1]. The motion slightly departed from the limit cycle returns by the effect of the attractor and the active tuning of the rhythm control. The process of the stabilization is described by isochron that is the contour of the phase over the whole area in phase space [2]. The property of the rhythm control for walking is entirely described by the isochron, thus the control mechanism by the rhythm can be described by the isochron.

Human body contains large number of segments including left and right limbs and trunk, and this high degree of freedom (DOF) has complicated the discussion of the limit cycle. Whereas, researches has shown the limbs and their segments moves rather coordinately and substantial DOF for walking has shown to be no more than two or three, thanks to the coordination. We have shown the limit cycle of the walking can be drawn in the three dimensional space spanned by the principle components using singular value decomposition (SVD)[3].

The aim of this research is to depict the isochron of human walking in the three dimensional phase space and to discuss the property of the walking rhythm reflecting the rhythm control. The experiment applying perturbation on human during walking is performed, and the returning process to the limit cycle is analyzed.

2. MATERIALS AND METHODS

Experimental device and procedure

Treadmill is set on the floor that can move horizontally by the equipped motor (Fig.1), and the perturbation is applied on the subject walking on the treadmill. The velocity of the treadmill is 4.0 [km/h] and the trial continues for 40 [s]. The floor moves from behind to front (arrowed direction) once in one trial. The amplitude of the perturbation is 30 [mm] and the velocity is 270 [mm/s].

Subjects are 3 healthy males. They are required to look at a small circle which locates far front of the subjects and the motions of their joints were measured with a motion capturing system. Reflective markers were attached to the subjects' skin overlying the following body landmarks of both hemibodies: ear tragus, upper limit of the acromion, greater trochanter, lateral condyle of the knee, lateral malleolus, second metatarsal head, and heel. The markers are also attached at treadmill and floor for measuring the translation of floor. The sampling rate is 500[Hz]. Subjects gave informed consent prior to data collection according to the procedures of the Ethics Committee of Doshisha University.

Fig. 1 Experimental device. Treadmill horizontally moves with servo motor equipped on the floor of the treadmill. Subjects walk on the treadmill suffering pulsed perturbation in arrowed direction once for one trial.

Calculation of limit cycle by SVD

The elevation angles of 8 segments (head, trunk, thigh(right,left), shank(right,left), foot(right,left)) referred as θ_{segment} are calculated. The motion of these 8 segments is mutually coordinated and the coordinate pattern of segments and that of time can be derived by SVD.

$$\Theta = \Theta_0 + \sum_i \boldsymbol{z}_i \left(\lambda_i \, \boldsymbol{v}_i\right)^{\mathrm{T}},$$

here Θ is a matrix whose column composed by the time series of θ_{segment} ($\Theta = [\theta_{\text{head}}, \theta_{\text{trunk}}, \ldots]$). Θ_0 is the matrix of the same size with Θ, which the temporal average of Θ is iteratively arrayed. z_i, v_i, λ_i are left singular vector, right singular vector and singular value of $\Theta - \Theta_0$ for each.

The level of singular values of walking has indicated that over 99% of the motion during 1 step is composed by 3 components, and the whole motion is constructed by the activation of time independent pattern z_i by $\lambda_i v_i$ as activation pattern. The orbit of $\lambda_i v_i$ draws a stable cycle in the space spanned by z_i as the coordination, and this stable cycle can be considered as a limit cycle of whole body motion [3].

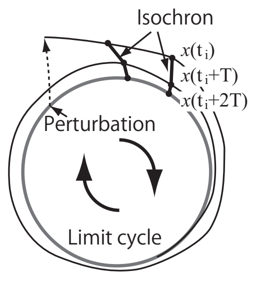

Fig. 2 The calculation procedure of isochron. Curved line around the limit cycle represents the returning route after perturbation. Isochron is derived by the relation among one point on the curved line $(x(t_i))$ with the points after cycles $(x(t_i+T), x(t_i+2T), \cdots)$. $x(t_i)$: state on the route at time t_i. T: cycle duration.

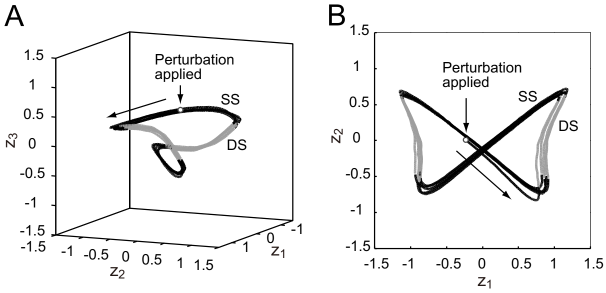

Fig. 3 Limit Cycle depicted on the z_1-z_2-z_3 space. The circle labeled by 'perturbation applied' represents the perturbation phase and the the orbit is drawn for 3 cycles after the perturbation. The part drawn by black line is single support phase (SS) and that drawn by gray line is double support phase (DS). Both figures A and B are the result of the same trial drawn from different viewpoints.

Derivation of isochron

Isochron is a contour of the phase spanned entire area in the phase space, where points on the same isochron has same phase with corresponding points on limit cycle. After the motion has slightly flied out from the limit cycle, the state returns with the orbit characterized by the isochron (fig.2 as image). The point $x(t_i)$ at time t_i and the points n cycle after that point $(x(t_i+nT))$ exists on the same isochron with different place. Thus the part of isochron can be calculated by connecting $x(t_i)$, $x(t_i+T)$, $x(t_i+2T), \cdots$.

In this paper, the lines for isochron is calculated for 100 points on the returning route of 1 trial. The experiment is duplicated for 75 times, thus the resulting isochron is depicted by 7500 lines.

3. RESULTS AND DISCUSSIONS

Limit cycle and the cycle of perturbation

Limit cycle of the whole body motion can be depicted in the 3 dimensional space of z_i. Before drawing the limit cycle in 3 dimensional space of z_i, we have confirmed whether the coordination of the cycle with perturbation z_i^{pert} is identical to that of cycle without perturbation z_i^{stable}. For this purpose the correlation between z_i^{pert} and z_i^{stable} is calculated. Then the correlation $z_i^{\text{pert}} \cdot z_i^{\text{stable}}$ was higher than 0.9 for every trial. This result indicated the perturbed cycle can be depicted in the same space.

Then, the orbit of whole body motion is drawn in the space spanned by z_1-z_2-z_3 as shown in Fig.3. The figure shows the orbit for three cycles starting from the perturbation labeled as 'perturbation applied'. Double support phase(DS) and single support phases(SS) was distinguished by their colors, both Figs. A and B displayed same one trial where the perturbation is applied during SS. As shown in figure B, the orbit gradually approaches the limit cycle after perturbation tracking different route among first cycle and two cycles after that.

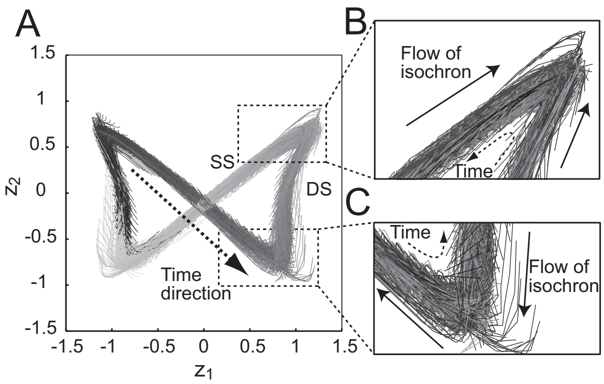

Fig. 4 The calculated isochron from the experiment. The colors on the figure A represents the phase of the isochron. A: the isochron with the same viewpoint with Fig.3B. Fig.B is the closeup of the Fig.A around hopping phase, and Fig.C is that around landing phase. The direction of isochron around hopping phase (Fig.B) changes discontinuously and not around landing phase (Fig.C).

Isochron

Fig. 4 shows the calculated isochron by connecting the points on orbit from 1st to 5th cycle after the perturbation. Isochron exists as surrounding the limit cycle and the direction of the flow of isochron heads opposite the flow of motion without the part of DS. In DS, the direction of flow of isochron changes at the center of DS, and the flow of isochron concentrated at the connection of DS and SS, i.e. hopping time (Fig.4B). This discontinuous of the flow cannot be observed around landing time(Fig.4C). This result indicates the phase is tuned by the hopping event against frontal perturbation.

4. CONCLUSION

Isochron of the human walking was depicted by the experiment with frontal perturbation. The derived isochron showed disconnection at hopping considered to be the effect of rhythm tuning.

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REFERENCES

[1] S.Yakovenko, et. al., *Biol Cyber*, Vol. 90, No. 2, pp. 146–155, 2004.

[2] Y. Kuramoto. Chemical Oscillations, waves, and Turbulence. Springer-Verlag, 1984.

[3] T.Funato, et. al., *Exp Brain Res*, Vol. 205, No. 4, pp. 497–511, 2010.