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# Reassessment of COM-ZMP Model for the Identification of Lateral Standing Controller of a Human

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*Abstract*— **This paper reports the result and discussion about our second experiment of standing motion measurement and analysis. We aim at identifying the standing controller of a human. In order to tackle the dynamical complexity of the human body, the COM-ZMP (the center of mass and the zero-moment point) model, which is widely used for designing the whole-body controller of humanoid robots, and a piecewise-linear controller is applied. In the previous experiment, the authors proposed a method to collect a sufficient number of loci of COM in a phase space for the identification of a controller, and showed that the human's standing behavior qualitatively has a similar property with the COM-ZMP model. It was also found, however, that the collected loci had large variability due to the uncertainty of convergence point and were partially inconsistent with the model, so that it was still difficult to identify the controller. Then, the authors reassessed the model and measurement protocol, and conducted the second experiment in order to improve the reliability of the measurement by visually presenting the referential point to subjects and by redesigning the protocol. As the result, more reliable loci to be processed of identification were obtained. It was also found that the effect of variation of the COM height due to the limitation of leg length, which was thought to be another source of the inconsistency, certainly existed but was not critical to model the human behavior.**

## I. INTRODUCTION

It is a big challenge to know how humans control their bodies to stabilize themselves against perturbations and to behave purposefully. The progresses in neuroscience and anatomy have been revealing functions of each component of human bodies including bones, muscles, nerves and the brain. The advancement of motion measurement and computation technologies have enabled detailed modelling of human bodies[1] and even monitoring the internal activities of muscles and nerves in realtime[2]. However, no matter how precisely the human motion is computed, it doesn't necessarily suggest a clear explanation about the principle of motor control of humans. The dynamical complexity of the human body which is characterized by hyper-redundancy, underactuatedness and structure-varying property makes the problem more difficult. Although many important studies related with the identification of human controllers have been reported, they basically discuss rather simple motions comprising only a couple of joints such as an arm-reaching[3], [4], [5] and a standing stabilization[6], [7], [8], [9]. In order to deal with the whole-body motion, one needs to tackle the above complexity.

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On the other hand, several techniques to control humanoid robots have been compiled in the field of robotics. It is known in particular that the macroscopic relationship between the center of mass (COM) and the center of pressure (COP), which is also named the zero-moment point (ZMP)[10], works for a hierarchical design of the whole-body controllers [11], [12], [13], [14], [15], [16], [17], [18], [19]. The authors[20] observed a human's lateral COM movements in a phase space and showed that the human's standing behavior qualitatively has a similar characteristics with the above relationship between COM and ZMP, which we call the COM-ZMP model hereafter. They also noticed, however, that the collected loci had large variability due to the uncertainty of convergence point and were partially inconsistent with the model, so that it was still difficult to identify the controller.

The above result has brought up a necessity to reassess the availability of the COM-ZMP model. The equation of the model involves four possibilities of the source of the inconsistency, one of which has already been found to be less in the previous work. Then, the authors redesigned the measurement protocol and conducted an additional experiment in order to investigate the other candidates, which are, the ambiguity on the referential point and the effect of variation of the COM height. The former issue was reduced by visually presenting the referential point to the subject and by applying a push-back procedure. The latter was examined by controlling and also uncontrolling the COM height during the motion measurements. As the result, more reliable loci on which the identification can be processed were obtained. It was also found that the effect of variation of the COM height due to the limitation of leg length was not critical to model the human behavior, althought it certainly existed. This paper reports the above results and discusses it.

## II. STANDING CONTROL SCHEME BASED ON COM-ZMP MODEL

This section first derives a controller model of a standing human on which the identification will be conducted. The dynamics of a humanoid, which could be either a real human or a humanoid robot, is represented by a complex equation of motion with a large dimensional generalized coordinates and inequality constraints originated from the limitation of reaction forces [21]. It is known, however, that the relationship between COM and ZMP well approximates the macroscopic characteristics of a humanoid through many studies on robot controls as referred in the introduction.

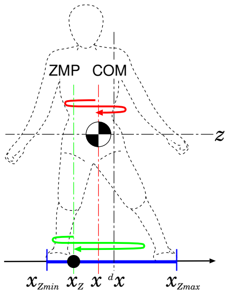
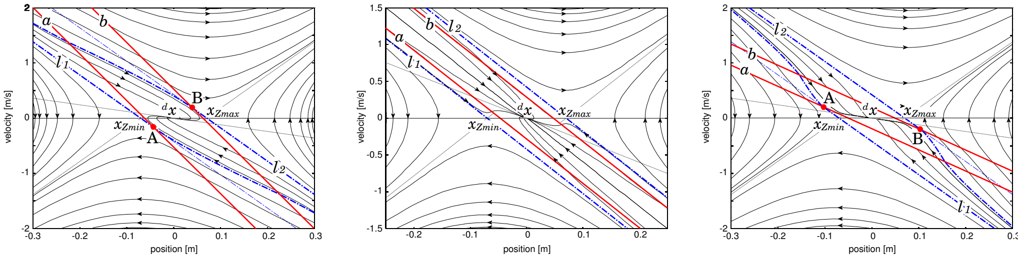



Fig. 1. COM-ZMP model of a lateral standing motion




(A) $q_1 = 0.2, q_2 = 0.6$ (B) $q_1 = 0.5, q_2 = 1.0$ (C) $q_1 = 0.2, q_2 = 2.0$

Fig. 2. Phase portraits of the COM-ZMP model and the piecewise-linear controller with respect to different eigenvalues

Let us consider a human motion in the lateral plane as shown in Fig. 1. The equation of motion is as follows:

$$\ddot{x} = \omega^2(x - x_Z) + \bar{a}_x \tag{1}$$

$$\omega \equiv \sqrt{\frac{\ddot{z} + g}{z}}, \tag{2}$$

where $x$ is the lateral position of COM, $x_Z$ is the lateral position of ZMP, $\bar{a}_x$ is an acceleration offset due to the effect of the torque about COM, $z$ is the height of COM with respect to the ground, and $g = 9.8$[m/s$^2$] is the acceleration due to the gravity. One can independently discuss motion in the sagittal plane as well from symmetry. Suppose the torque about COM is sufficiently smaller to be neglected than that due to the translational movement of COM about ZMP (i.e. $\bar{a}_x \simeq 0$), we get the equation of motion[15] as

$$\ddot{x} = \omega^2(x - x_Z). \tag{3}$$

Whichever model we stand on, ZMP is constrained in the supporting region as

$$x_{Z\min} \leq x_Z \leq x_{Z\max}, \tag{4}$$

where $x_{Z\min}$ and $x_{Z\max}$ are the right and the left ends of the supporting region in $x$-axis, respectively. The above constraint comes from the unilaterality of reaction forces, namely, the fact that any attractive forces cannot act at any contact points.

Sugihara[19] proposed a controller in which the desired ZMP ${}^dx_Z$ is decided by a piecewise-linear feedback of COM state as

$${}^dx_Z = \begin{cases} x_{Z\max} & (\text{S1:}\tilde{x}_Z \geq x_{Z\max}) \\ \tilde{x}_Z & (\text{S2:}x_{Z\min} < \tilde{x}_Z < x_{Z\max}) \\ x_{Z\min} & (\text{S3:}\tilde{x}_Z \leq x_{Z\min}) \end{cases} \tag{5}$$

$$\tilde{x}_Z \equiv {}^dx + k_1(x - {}^dx) + k_2\dot{x}, \tag{6}$$

where ${}^dx$ is the referential position of COM, and $k_1$ and $k_2$ are feedback gains. If the actual ZMP, which works as the input to the system, is manipulated to track the desired ZMP, the feedback system becomes

$$\ddot{x} = \begin{cases} \omega^2 x - \omega^2 x_{Z\max} & (\text{S1}) \\ -\omega^2(k_1 - 1)(x - {}^dx) - \omega^2 k_2 \dot{x} & (\text{S2}) \\ \omega^2 x - \omega^2 x_{Z\min} & (\text{S3}) \end{cases}. \tag{7}$$

If we suppose that the COM height is invariant during the motion, namely, $z$ is constant, $\omega$ is also constant and accordingly the system is piecewise-affine. In the case of robot control, the gains can be defined based on the pole assignment technique. Suppose the desired poles in (S2) are given as $-\omega q_1$ and $-\omega q_2$. Then, $k_1$ and $k_2$ are

$$k_1 = q_1 q_2 + 1, \quad k_2 = \frac{q_1 + q_2}{\omega}. \tag{8}$$

Fig. 2 shows phase portraits of the feedback system with respect to some different poles. The red lines $a$ and $b$ in the portraits mean the switching plane between (S1), (S2) and (S3); the region between $a$ and $b$ is (S2). (S1) and (S2) are separated by $a$, and (S2) and (S3) by $b$. The blue dotted areas are stable regions, where COM stably converges to the referential position.

Although this controller is simple with a small number of parameters for modelling the human behavior, it has the following virtues comparing to the previous standing models [6], [7], [8], [9].

1) It is almost free from body constitution of the subject, so that it suggests a macroscopic understanding of the whole-body behavior.
2) Effects of body constitution appears as perturbations, which is rather easily separated from the dominant behavior of the system, so that it suggests a hierarchical structure of the controller.
3) It explicitly deals with the dynamical constraint due to the unilaterality of reaction forces, which is hard when observing only behaviors of each joint.
4) It enables quantitative evaluation of the controller. Stabilizability and responsivity are quantified by the system eigenvalues.

## III. Visualization of Lateral Standing Behavior and Identification of Controller

When considering to apply the model in the previous section to the identification of a human controller, many loci of COM in a phase space have to be collected. For this purpose, the authors[20] conducted an experiment, which is summarized in this section.

It is not easy to collect a sufficient number of loci which cover broad area of the phase space, since in regular situations a subject basically starts his/her motion only from a stable resting state, namely, he/she can start his/her motion only from points on the line $\dot{x} = 0$ between $x_{Z\min}$ and $x_{Z\max}$. The loci observed under this condition exist within a very limited area near the point of equilibrium.

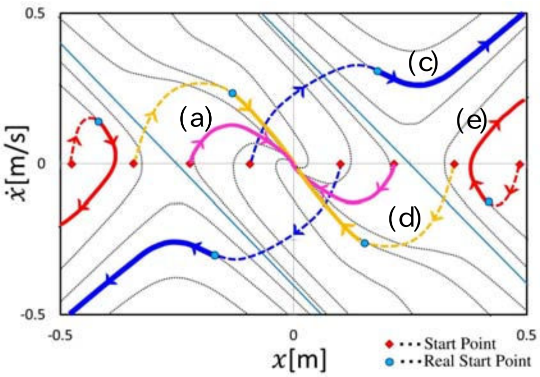



Fig. 3. An expected phase portrait of a standing motion in COM state space, where dashed lines are trajectories of preparatory motions which carries COM to the desirable initial state.

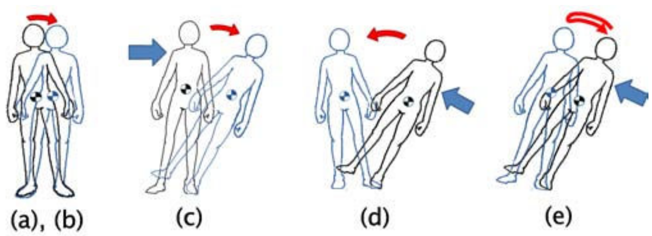



Fig. 4. Illustrations of examined motions in Fig.3: (a) is a regulatory motion to compensate the initial offset of COM, (c) is a divergent behavior on which the subject eventually falls down, (d) is a regulatory motion to the referential point from a distance, and (e) is a falling motion. In order to carry COM to desirable initial state, an external force (blue arros) has to be applied to the subject.

In order to measure motions in a distance from the point of equilibrium, we predict behaviors to be observed in each area of the phase space based on the phase portrait in theory as Fig. 2. Then, we add preparatory motion to each trial in order to accelerate COM to the desirable initial state as depicted in Fig. 3. (a) is a group of loci of standing motions where COM is moved to the referential position from another position. (c) is that on which the subject eventually falls down. He/she has to carry him/herself to unstable area for those motions. (d) is that for stable motions starting from states in a distance of the point of equilibrium. The subject should initiate his/her motion from outside of the supporting region with a help of a holding platform, and accelerate him/herself so much that he/she reaches the desired state. (e) is that for unrecoverable falling motions, which also require a help of a holding platform in the peparatory motion. Each type of motion is illustrated in Fig. 4. A common process in the above is that the subject starts motions from resting states in some cases assisted by a platform and accelerates him/herself until he/she reaches valid trajectories. The partial loci of those preparatory motions before valid start points should be discarded.

The above idea was examined in a motion capture system. Retoreflective markers are attached to the subject's body so that his/her motion is captured by optical cameras. At the same time, the reactive forces are measured by force plates during motions. In order to accelerate the body to the desired state in preparatory phases, a ladder is set next to the subject as an assistive platform. The force exerted to it can also be

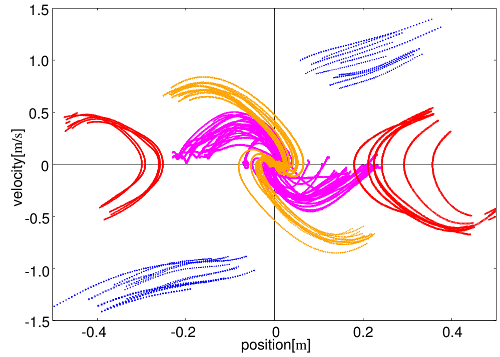



Fig. 5. COM loci measured through the experiment

measured by another force plate, which is used to detect the valid start points of motions. The subject regulates his/her motions by adjusting his/her stance to markers put on the force plates and by seeing a marker of the referential point put in front of him/her.

The subject was a 23-year-old male, who was 175[cm] tall and weighed 73[kg]. His kinematics and dynamics were modeled and identified before the experiments based on a method proposed by Ayusawa et al.[22]. For the motion capture system, MAC3D (Motion Analysis Inc.) was used to measure 3D loci of a set of the retroreflective markers attached to the subject's whole-body every 5[ms], which were converted to a locus of the whole-body configuration through the inverse kinematics. The locus of COM was computed through the forward kinematics based on the subject's mass property. Measurement noises were reduced by a second-order Butterworth filter with 2[Hz] of cutoff frequency. By numerically differentiating it, a history of the velocity and acceleration of COM were computed. The locus of ZMP was also computed from a history of the reaction forces. Based on the record of the reaction force exerted from the ladder, the valid start point of valid motion was found and the segment of preparatory motion was deleted. 8 loci for each type of the above 4 motions (a), (c), (d) and (e) were collected in symmetric manners with respect to the point of equilibrium. Hence, the number of the loci was 64 in total.

Fig. 5 shows the resultant loci of the experiment, where the referential position was set to be the original point, namely, ${}^{d}x \equiv 0$. We see that it is qualitatively similar to the phase portrait Fig. 2 so that the COM-ZMP model with the piecewise-linear controller reasonably approximates the actual human behavior to some extent. One may find, however, that the loci cross each other at many points, meaning that the variance of loci is not negligible. Then, we applied the least-square method to identify both the system parameters ($\omega$, $x_{Z\min}$ and $x_{Z\max}$) and the control parameters ($k_1$ and $k_2$). Note that the system is linear with respect to $\omega^2$, $\omega^2 x_{Z\min}$, $\omega^2 x_{Z\max}$, $\omega^2(k_1-1)$ and $\omega^2 k_2$, so that the computation is basically the linear regression. Fig. 6 shows the results, where the measured loci are superposed on the phase portrait of the identified systems. Some of them are favorable in terms of accuracy as (A) and (B), while others are not as (C). (D) is that of the identified system from all stable loci, which considerably mismatches from

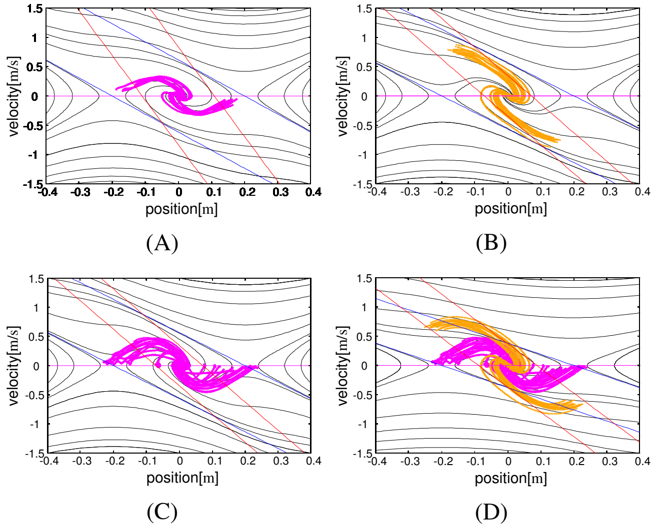



Fig. 6. COM loci and identified control systems

the measured data due to such an unfavorable group.

## IV. Reassessment of the Model and Measurement Protocol

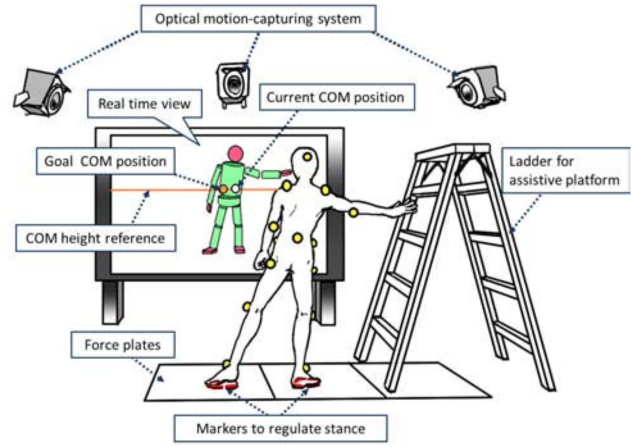
Through the earlier experiment described in the previous section, the authors learned that the identified results have mathematical inconsistency with the theoretic COM-ZMP model, whereas the model qualitatively resembles a human standing dynamics. Eqs.(3) and (7) involves four possibilities of the origin of the inconsistency, namely,

- P1) the effect of $\bar{a}_x$, which was neglected in Eq.(3),
- P2) the effect of variation of $\omega$, which was supposed to be constant during motions,
- P3) the effect of ${}^{d}x$, which was not certainly presented to the subject during the experiment, and
- P4) the effect of non-linearity of the controller, which was not modelled so far.

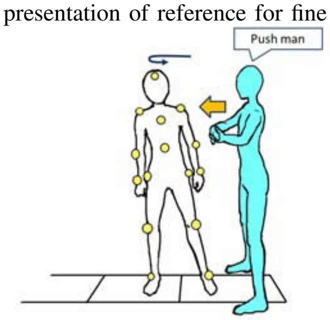
Now, the problem is to scrutinize the above possibilities and to reassess the model before collecting more loci of many subjects.

P1) has already been investigated in the previous work[20] as follows. As long as we suppose Eq.(3), the effect of $\bar{a}_x$ appears as the residual $\varepsilon \equiv \ddot{x} - \omega^2(x - x_Z)$. Since $\bar{a}_x$ is the rate of the torque about longitudinal axis per the COM height, a large portion of which is produced by the inertia of legs, it should be associated with the sideward movement of COM under the fixed stance. Then, we calculated the self-correlation between $\varepsilon$ and $\omega^2(x-x_Z)$ for each group of (A), (B) and (C) in Fig. 6. The result is shown in Table I, from which we can conclude that they are almost uncorrelated and the possibility P1) is not a strong candidate of the origin.

In order to discuss the possibilities P2) and P3), we redesigned the motion measurement protocol as follows. As Fig. 7(A) illustrates, a monitor on which the computed body configuration and the center of mass are displayed in realtime is put in front of the subject in motion. The referential position also appears in the same monitor, and the subject is guided to carry his/her COM to it. It helps to see the possibility P3). The referential height of COM is also drawn




(A) Visual presentation of reference for fine control COM




(B) Push-back test to see impedance around point of equilibrium

Fig. 7. Redesigned motion measurement protocols

TABLE I

SELF-CORRELATION BETWEEN $\varepsilon$ AND $\omega^2(x - x_Z)$

| Group of loci | (A) | (B) | (C) |
|---|---|---|---|
| self-correlation between $\varepsilon$ and $\omega^2(x - x_Z)$ | 0.034 | 0.01 | 0.06 |

on the monitor, on which the subject can visually control his/her COM height. It is for investigating P2). Another idea is to push the subject sideward while he/she stands still. This works for the subject to consciously keep the referential position at the same point, so that the resulted motions are expected to inhibit deviations of the reference and purely exhibit the effect of state feedback, through which one can also check the possibility P3). If there still remain an inconsistency, it means that the linear state feedback can hardly approximate the human's standing controller and we have to consider the possibility P4).

## V. Result and Discussion

Based on the protocol proposed in the previous section, the second motion measurement experiment was conducted. The subject was a 21-year-old male, who was 181[cm] tall and weighed 70[kg]. The same sets of examined motions with the previous experiment under the condition with both uncontrolled and controlled COM height were measured. Hence, the number of the collected loci was 128 in total. The mass properties of the subject's whole-body was identified as well. Fig. 8 shows snapshots of scenes of the experiment. (a), (c), (d) and (e) correspond to those in Fig. 4, respectively.

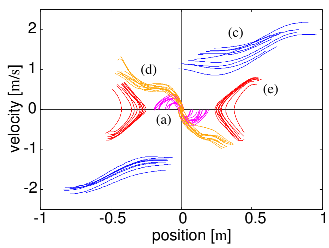
(a) COM movement around the referential position

(c) over-accelerated movement, eventually falling down

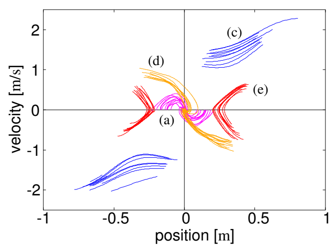
(d) recovery movement from a point beyond the stance

(e) unrecovered movement outside of the stance

Fig. 8. Snapshots of experimental scenes




(A) COM height uncontrolled




(B) COM height controlled

Fig. 9. Loci of COM of standing motions

TABLE II
IDENTIFICATION RESULTS WITH UNCONTROLLED COM HEIGHT

| Parameter | Identified value | Applied motion type |
|---|---|---|
| $\omega$ | 2.27 | (a)(c)(d)(e) |
| $x_{Z\min}$ | -0.22 | (c)(e) |
| $x_{Z\max}$ | 0.21 | (c)(e) |
| $k_1$ | 2.03 | (a)(d) |
| $k_2$ | 0.67 | (a)(d) |
| Ave. of squared error | 0.55 | |

TABLE III
IDENTIFICATION RESULTS WITH CONTROLLED COM HEIGHT

| Parameter | Identified value | Applied motion type |
|---|---|---|
| $\omega$ | 2.74 | (a)(c)(d)(e) |
| $x_{Z\min}$ | -0.20 | (c)(e) |
| $x_{Z\max}$ | 0.18 | (c)(e) |
| $k_1$ | 1.94 | (a)(d) |
| $k_2$ | 0.45 | (a)(d) |
| Ave. of squared error | 0.25 | |

As the result, two sets of loci were obtained as Fig. 9(A) and (B), where the referential position is set to be the original point, namely, ${}^{d}x \equiv 0$. (A) is one with uncontrolled COM height, while (B) is with controlled COM height. For both cases, the loci ran with less crossings than in Fig. 5, which is thought to be owing to the certainly presented referential position. Though the global structure of the measured behaviors in the two cases are similar, the difference of the condition qualitatively appears in the two figures, namely, the loci of (A) in a distance from the point of equilibrium are distorted from the theoretic curves of the linear dynamics, while that of (B) are not.

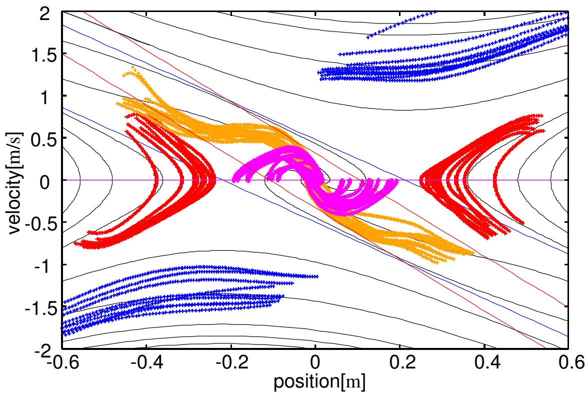
Then, we applied the least-square method to identify both the system parameters and the control parameters. The results are summarized in Table II and III, where the average of squared error of each result is only for a reference to compare the two and the value itself doesn't physically make sense. Fig. 10 shows the phase portrait of the identified systems on which the measured loci are superposed as well as Fig. 6. Obviously, they are more favorable in terms of accuracy than Fig. 6. Thus, P3) the effect of ${}^{d}x$ in the previous section was the strongest candidate which caused the inconsistency in the previous result. On the other hand, P2) the effect of variation of $\omega$ also certainly affected the behavior since the average of squared error was reduced by controlling the COM height. The remaining loci other than the distorted portion, however, is still able to provide sufficient data set to be identified, so that it is not critical to model the human behavior.

Fig. 10 raises another problem to be considered. As defined in Sugihara[19], once the COM state goes out of the stable region ($\simeq$ the region between the blue lines), it will eventually diverge. Conversely, if the COM starts from a point within the same region, it never goes out. In the result, some of the loci came back from outside of the nominal stable region and converged to the point of equilibrium, while others went out of the region. One may guess that it might be due to the neglected torque about COM associated with arm swings, for example. However, the authors have another hypothesis that the gradient of the asymptotic lines might depend on the direction of movement of the COM and the stable region is to be redefined. It will be discussed in the future work.

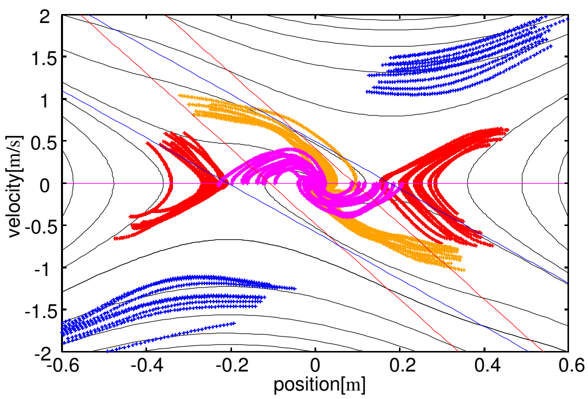
## VI. CONCLUSION

Based on the previous motion measurement and identification, we reassessed the system model and the controller, and redesigned the measurement protocol in order to find out the source of inconsistency between the model and the real human behavior. As the result, an ambiguity of the referential position for the subject was thought to be the most possible of the four candidates that caused the inconsistency. Actually, we succeeded to collect more reliable motion loci and to improve the accuracy of the identification by visually presenting the referential position to the subject.

In this work, the parameters were computed through a batch identification based on the least-square method. Eq.(6) implies that the controller may switch even in stably converging motions, which means that the governing system




(A) COM height uncontrolled




(B) COM height controlled

Fig. 10. COM loci and identified control systems

equation might vary during the motion and the parametric identification is more complicated. The authors[23] dealt with this problem in another work.

To know the motional properties of humans in a quantitative way helps medical diagnoses, athletic trainings, rehabilitations, ergonomic designs and so forth. A mathematical model of a human controller is also utilized for designing artificial systems interacting or involving humans such as human interfaces, prostheses, production systems and even social systems. The authors hope their work will contribute to various applications.

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