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Analyzing the ”Knack” of Human Piggyback Motion Based on Simultaneous Measurement of Tactile and Movement Data as a Basis for Humanoid Control

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***Abstract*— To help with care work and rescue operations, it is necessary for humanoid robots to have the ability to transport humans steadily and gently. In this research we consider "piggyback" motions for transporting humans. Most people can perform this motion, allowing us to measure and analyze piggyback motions of human subjects using tactile sensing and whole body movements to design whole body contact control. One interesting result of this investigation is that frictional forces are skillfully controlled by the carrier. In the first experiment, we study a "knack" that allows the carrier to reposition the rider. In the second experiment we verify the effectiveness of the knack in achieving the repositioning result. We also studied the principle of the repositioning motion, and found that it is similar in many ways to a jumping motion. Then we confirmed the validity of our modeling assumptions using a dynamical simulator.**

I. INTRODUCTION

Humanoid robots are expected to several different operations: cleaning, laundry, care work and various other real world tasks[1], and many people have friendly feeling toward humanoid robots. Then it is widely hoped that humanoid robots will be active in the field of care work, and this motivates research in which humanoid robots are developed for handling heavy objects or human like bodies[2], [3], [4]. A critical requirement for robot care workers is gentleness: the robot must move steadily, but also softly and without harming the relatively delicate human. Thus, brute force robotic methods of grasping and moving the human body are completely inadequate.

To achieve the goal of steady and gentle handling of human bodies by humanoid robots, new control methods must be developed. In this paper we consider the task of "piggyback motion", which is important in disaster relief and care work, and may be useful in various other situations as well. This task is difficult because it involves a complex frictional force between the robot and human body, and because the human body is a flexible and multiply-linked structure. Little research has been done which considers the full complexity of this type of motion.

Despite the significant complexity of the piggyback motion, most people can perform it without any special technique or training. We believe that humans have a natural method of skillfully controlling contact states, which allows them to perform piggyback motions easily. In principle, because humanoid robots have the same body structure as humans, it should be possible for such robots to use the same human method of controlling contact state while performing piggyback motion. In order to understand the human method of contact state control, in this research we measure and analyze the piggyback motion with human subjects. There are some previous studies of measurement of human body and motion for robot controller design. The legged robots and humanoid robots developed by HONDA execute bipedal locomotion based on the result of analysis of human locomotion[5]. Miura et al. analyze a human "twirl" motion, which exploits the friction between feet and floor, and implement the twirl motion using the humanoid robot HRP-2[6]. This study is very interesting because this motion uses the friction force effectively. Yamamoto et al. study the problem of handling of human bodies: they measured techniques for lifting human bodies, and found the knack for the lifting motion[7]. But they have not yet implemented such lifting motions using humanoid robots. In the work of [5] and [6], the motions are studied by analyzing the contact between foot and floor. On the other hand, most people use various contact states to lift the human body[7]. However, Yamamoto et al. didn't measure the tactile sensing between human and dummy. Hosaka et al. developed a tactile sensor suit for measuring a baby-carrying pose, and analyzed the differences in movement and tactile sensing pattern between

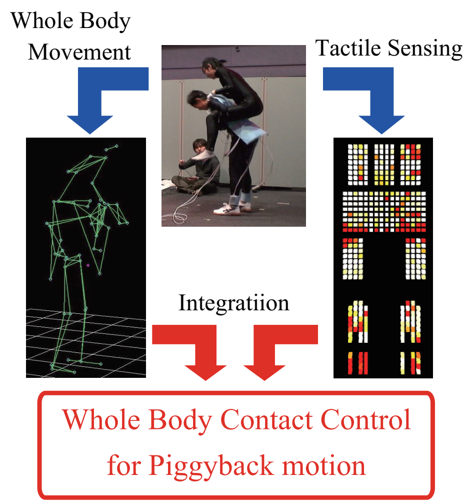

Fig. 1. To design a Whole Body Contact Control, whole body movements and tactile sensing need to be measured simultaneous.

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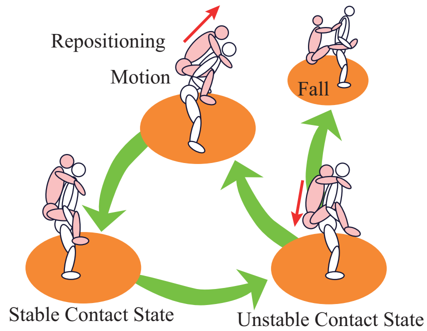

Fig. 2. Image transferring each state: stable state, unstable state, falling state and repositioning motion.

mothers and amateurs[8]. In this research, only upper body movement is measured.

We think that the tactile sensing and whole body movement are very important for the piggyback motion, because most people execute this motion using a wide area contact between the two bodies. In this paper we simultaneously measure both the human whole body movement and the tactile pressure. Based on the analysis of the piggyback motion, we discuss a new method where humanoid robots control the contact states. Figure 1 shows the outline of the idea of integrating tactile and movement data to achieve "whole body contact control".

II. MANEUVERING CONTACT STATES IN PIGGYBACK POSTURE

The ultimate goal of this research is the realization of humanoid robots that can handle the human body to help with care work or rescue operations. This task is quite difficult, for reasons which we now discuss. From now on we refer to the person (or dummy) being carried as the "rider" and the person or robot doing the carrying as the "carrier".

First, a complex friction occur between the bodies of rider and the carrier, and the piggyback motion is underactuated mechanical system. Therefore it is extremely difficult to control the state of rider, and to observe it completely.

Second, when the carrier begins to walk, if a disturbance occurs the rider may begin to fall. Then the carrier needs to reposition the rider. However, designing a control scheme for this motion is difficult for the reasons mentioned above.

In the piggyback motion we consider, complex frictional forces play a very significant role. Most humans can deal with this task. Our hypothesis is that the carrier does not continuously calculate and compensate for the full frictional force, but rather uses an important pose point to control the friction. Following Kuniyoshi et al. we call this important pose point a *knack* [9], [7]. The knack is defined as a simple control method which determines the success or failure of a complex task. In particular, we believe that there is a knack for repositioning motion occurs when the carrier changes from the unstable contact state to the stable contact state. At this knack, the carrier controls the complex friction force to perform the repositioning motion. The image of stable contact state and unstable contact state is shown in Fig. 2.

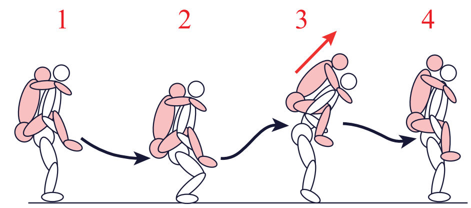

Fig. 3. A sequence of the repositioning motion. 1, 2, 3 and 4 show the unstable contact state, the state bending the knee, the state moved a rider and the stable contact sate.

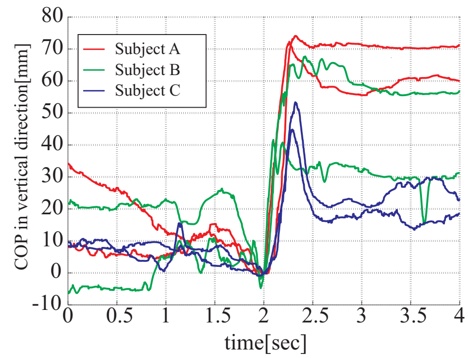

Fig. 4. The trajectories of COP when carriers perform the repositioning motion. The horizontal axis is time[sec], the vertical axis is the COP[mm].

III. EXPERIMENT I: REVEALING THE STRATEGIES FOR REPOSITIONING IN PIGGYBACKING

In the previous section, we described about knack changing from the unstable contact state to the stable contact state. In this section we measure the movement and tactile sensing data related to this knack.

A. Purpose and conditions

The purpose of this experiment is to consider the knack where the carrier repositions the rider from the unstable contact state to the stable contact state. In this study, the carriers are three young adult males, and the rider is also a young adult male weighing 58 [kg]. We use the optical motion capture system: "VICON". We use the 11 cameras, and the temporal resolution is 120[Hz].

We use the tactile sensing system developed by Ohmura et al[10]. This sensor is fitted on the back, shoulder, hip and sole of subjects.

In this experiment, each carrier gives the rider a piggyback ride with the head bent forward. At some point the carrier rises to his full height, so that the rider begins to fall. To compensate, the carrier performs the repositioning motion.

B. Result and Discussion

Figure 3 shows a sequence of the repositioning motion taken from a video of the experiment.

To research the contact state, Fig. 4 shows the COP (Center of Pressure) of each subject, as the repositioning motion is performed. This motion is executed at time= 2.0[sec]. The red, green, and blue lines show the trajectories of carrier subjects A, B, and C respectively.

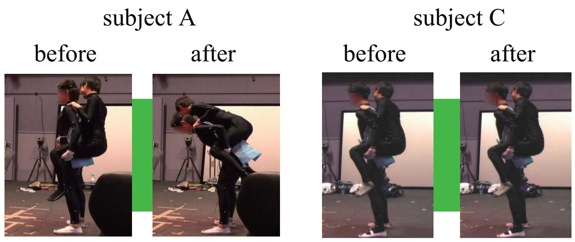

Fig. 5. The appearances of the before and after repositioning motion. The left side two photos are subject A, the other side photos are subject C.

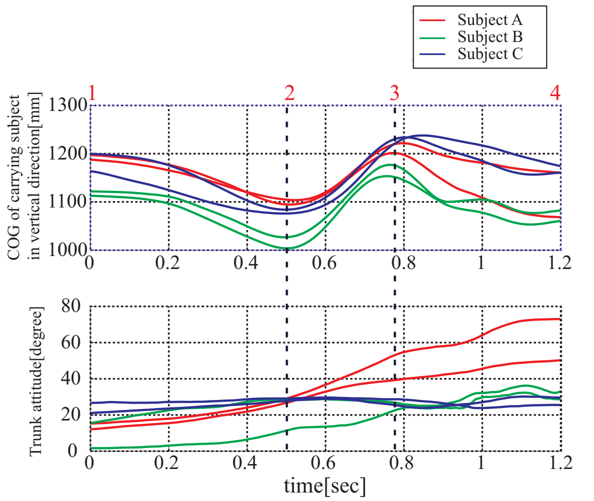

Fig. 6. The trajectories of COG and attitude angle of upper body. Top: COG, bottom: attitude angle of upper body.

We find clear differences among three subjects. The elevated value of the red trajectories are higher than the other trajectories, while the minimum value of the red is smaller than the blue trajectories. Furthermore, the position of the red trajectories has lower variance than the green trajectories after the repositioning movement, and the strategy of the red subject is high assurance. Therefore, we believe that the subject A understands the knack, such that the effect of the repositioning motion is achieved. On the other hand, the repositioning motion of subject C has poor efficacy. The repositioning motion of subject A and subject C are shown in the Fig. 5, which shows positions before and after the repositioning motion.

To further analyze the difference between the carrier subjects, Fig. 6 shows the COG (Center Of Gravity) and attitude of upper body. The state of 1, 2, 3 and 4 in Fig. 6 correspond the state of 1, 2, 3 and 4 in Fig. 3. Each COG trajectory is similar, especially on the interval between 2 and 3, but the upper body angle difference between subject A and the other subjects is quite significant. For the red trajectory, the attitude angle increased substantially in the interval between 2 and 3, while the change of the other trajectories was less significant.

From Fig. 5 and 6, we believe that increasing the attitude angle of upper body is important for the success of the repositioning motion. When the carrier bends forward and down, if the angle at the low point is more than 40[degree], his hip goes up and the rider is thrown up by this motion. Moreover, the rider is moved a long distance using little power because he is moved in a horizontal direction, avoiding gravitational resistance. Additionally, the rider is easily caught because the carrier has bent forward. Therefore, the knack that the effect of the repositioning motion is achieved is as follows:

- Using the hip to launch the rider up.
- Bending forward to catch the rider.

In the next section, we verify the effectiveness of this knack.

IV. EXPERIMENT II: VERIFICATION AND QUANTIFICATION OF THE "KNACKS" OF REPOSITIONING IN PIGGYBACKING

We discussed about knacks of repositioning motion in the previous section. In this section, we verify whether the elevated value of the carrier is improved by using these knacks. Furthermore, we will consider the stable and unstable contact state of the piggyback motion and investigate the border between the two.

A. Purpose and Conditions

The purpose of this experiment is verification of the knacks explained in previous section. When the carrier determines that the risk of dropping the rider is high, the carrier performs the repositioning motion. In this experiment we also discuss a criterion which can be used to judge whether the rider is falling.

In this experiment, the carrier subjects are ten healthy males and the rider subjects are two healthy males whose weight is 58[kg]. They are undergraduate and graduate students of ages ranging from 20 to 27. They are informed about the experiment and signed a informed consent form.

The piggyback task of this experiment is that the carrier carries the rider on his back, while walking backward and forward for 30 [sec]. Additionally, we give the carriers the following instructions. In the first experiment, "Please don't allow the rider to drop while walking. " Next, in the second experiment, "If you think the rider is falling, please reposition him using only your arms. " Finally, in the third experiment, we explain the knacks of repositioning motion described in section III, and instruct the carrier: "If you think that it is necessary to reposition, please perform the repositioning motion using the knacks." We will call first condition "without instruction", the second condition "using only arms", and the third condition "with knacks". Each subject performs this task for 18 times (6 trials for each instruction).

We use a motion capture system, a whole body tactile sensor and a pressure distribution sensor for the foot soles. The motion capture system and tactile sensor are similar to section III. The marker positions of the optimal motion capture system are shown in Fig. 7. There were 35 markers on the carrier (Fig. 7-(a)) and 18 markers on the rider (Fig. 7-(b)). We believe that hand based tactile sensing is also important, so the tactile sensor of the hands is added. Then a number of total elements of tactile sensor is 488 (back: 160, waist: 272 and each hand: 28). But the pressure on the

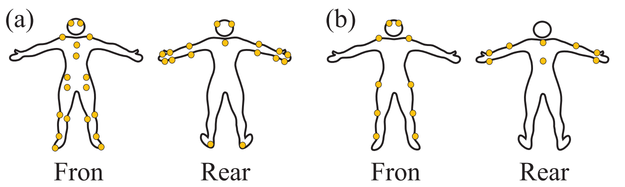

Fig. 7. The maker position. (a): the carrier. 4 on the head, 3 on the trunk, 2 on the waist, 1 on the each shoulder, 2 on the each elbow, 4 on the each hand, 1 on the each thigh, 2 on the each knee and 3 on the each foot. (b): the carried subject. 2 on the head, 2 on the trunk, 1 on the each shoulder, 2 on the each hand, 1 on the each thigh, 1 on the each knee, 1 on the each ankle.

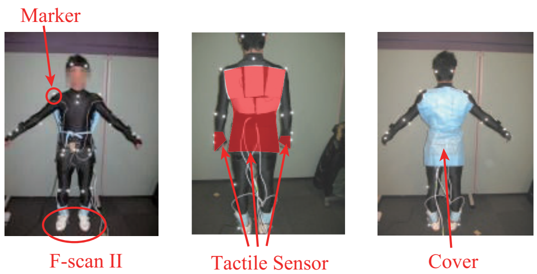

Fig. 8. The appearances of the carrier with all makers, F-scan II and tactile sensor. The tactile sensor is fitted on the red area of the central photo, this sensor are covered with the blue cloth (right side photo).

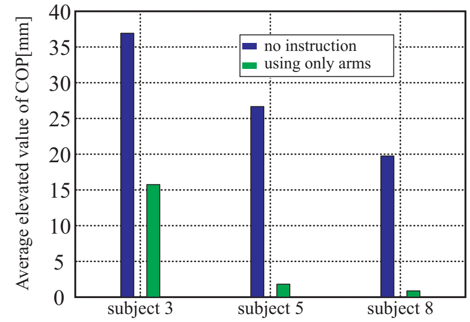

Fig. 9. The average elevated value in COP altitude for the case of "no instruction" and "using only arms".

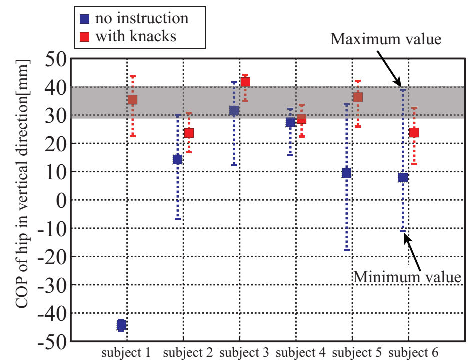

Fig. 10. The each average COP of 6 subjects to compare "no instruction" and "with knacks". The square is the average value, the top of bar is maximum and the bottom of bar is minimum.

feet is so strong that the tactile sensor could not be used. So we use a F-scan II pressure distribution sensor (Nitta Corp.) to analyze the pressure and COP for each foot. This sensor is a insole-shaped sheet and pressure is measured in 5 [mm] resolution and temporal resolution is 120 [Hz]. The appearance of carrying subject is shown in Fig. 8.

B. Result and Discussion

Firstly, we compare "without instruction" and "using only arms". We expected that different strategies for the repositioning motion of the first experiment would appear in the second experiment, as some subjects execute the same repositioning motion as the first experiment while others do not. Our hypothesis is that humans naturally perform the motion studied in the first experiment to reposition a piggyback rider. So, we compare the results of the rider motion in the first and second experiments. Figure 9 compares the average increase in COP altitude for the case of "no instruction" and "using only arms".

We clearly find that the "no instruction" repositioning motion is more effective than "using only arms." The only arms strategy produces a very small elevation because of the frictional force between the rider and carrier. Thus, it is necessary to overcome the friction for repositioning the carried person, and the full-body (no instruction) repositioning motion can do it.

Next, we discuss about effectiveness of the knacks explained in the section III. Then, the COP of "with knacks" after repositioning is compared with the COP of "without instruction" after repositioning. The average of the each COP is shown in Fig. 10. This graph shows the average value, maximum value and minimum value of 6 subjects, the blue is "no instruction", the red is "with knacks". The origin is iliospinale posterius. The gray region in the graph is the area on which the red data concentrate, which we describe in detail below.

The variance of the red average is smaller than the blue, so we conclude that the "with knacks" strategy allows easy convergence to the goal area. The average elevated value of the red datum is lager than the blue datum. This shows the effectiveness of the knacks described in section III.

We explained the knacks of the repositioning motion, but the principle of this motion has not yet been discovered. To understand the principle of the repositioning motion, Fig. 11 shows the COG, acceleration of COG, the pressure distribution of the hip, and the pressure value of the feet. Only one sample is shown and the others are similar to it.

In Fig. 11-(a), the acceleration of carrier is nearly $-9.81[m/s^2]$ (gravitational acceleration). Then the carrier executes a jump-like motion, the acceleration of rider becomes about $-9.81[m/s^2]$ (Fig. 11-(b)), and at the same time the pressure value of the hip becomes very small. Therefore, we think that the carrier performs the jump-like motion to reduce the hip pressure, which reduces the friction force and allows the rider to be moved with a small force. For this motion to work, it is necessary that there is time lag between the acceleration of carrier and rider. If time lag is 0 [sec], the carrier and rider move simultaneously, and the relative displacement between them doesn't occur. The cause of this time lag is described in the next section.

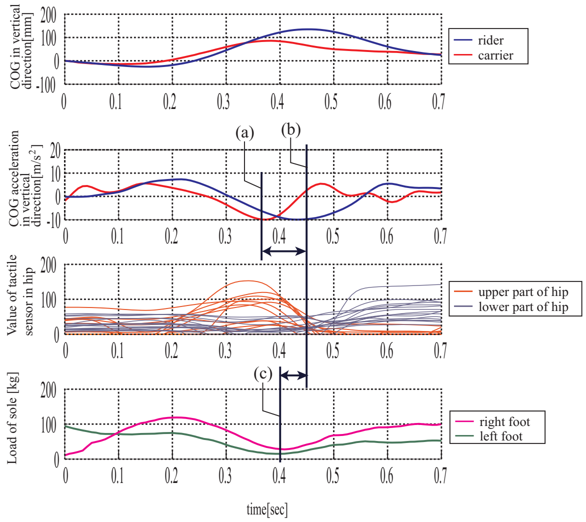

Fig. 11. The trajectories of COG, acceleration, pressure of waist and each foot. First row: the position of COG, second row: the acceleration of COG, the third row: the pressure of upper waist and lower waist and forth row: the pressure of each foot. (a): the acceleration of carrier is $-9.81[\mathrm{m/s}^2]$, (b): the acceleration of rider is $-9.81[\mathrm{m/s}^2]$ and (c): the pressure of each foot decreases.

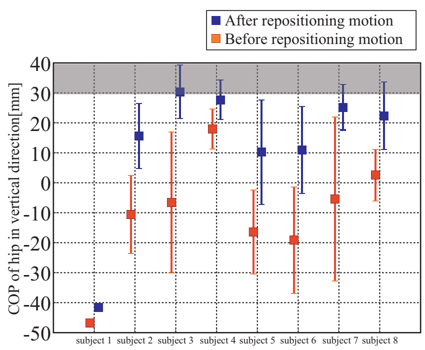

Fig. 12. The each average COP of 8 subjects to compare before and after the repositioning motion. The square is the average value, the bar is the variance value.

C. Discussion about keeping a stable contact

To find a criterion that determines whether the rider falls, the average data of COP in the first experiment of the repositioning motion is shown in Fig. 12. The horizontal axis is each subject. The squares indicate averages, while the bars show values for the variance. The blue data are the average of COP after the repositioning motion, the orange data are the average of COP before the repositioning motion. The blue datum are same as Fig. 10.

When the COP falls below the origin (iliospinale posterius), most subjects perform the repositioning motion. So we believe that the carrier determines that the rider is falling when the COP of the back slips below this point. Moreover, as shown in Fig. 10, we conclude that the COP tends to converge the gray zone. The COP of some subjects has hardly changed while waking backward and forward for 30[sec]. The carriers hold the rider between the thigh of rider and a region of the carrier's waist between the rib and pelvis. We believe that this part is stable contact part for the human.

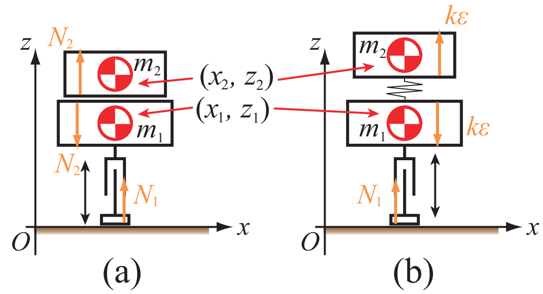

Fig. 13. The movement model of the repositioning motion. (x_1, z_1), (x_2, z_2) are the position of COG, m_1, m_2 are mass, N_1, N_2 are normal force, g is gravitational acceleration and $k\varepsilon$ is the elastic force. (a): the model without elasticity, (b): the model with elasticity.

V. MODELING REPOSITIONING MOTION

We explained that non-contact state is brought about by a jump-like motion executed by the carrier, which also creates a relative displacement between carrier and rider. However, we have not yet discovered the principle of this motion. So we now propose a model of the motion, based on some assumptions which are then verified with a dynamical simulator.

A. The Model of the Motion

The carrier is modeled as a single mass with a prismatic joint for the legs, and the rider is approximated as a rigid body. To discuss purely a dynamical feature of repositioning motion, we ignore a friction force between two bodies. This model is shown in Fig. 13-(a). Therefore, we get the following motion equations.

$$m_1\ddot{z}_1 = N_1 - N_2 - m_1 g \tag{1}$$

$$m_2\ddot{z}_2 = N_2 - m_2 g \tag{2}$$

Where, m_1 is the mass of carrier, m_2 is the mass of rider, N_1, N_2 are normal forces, and g is gravitational acceleration. However, this model does not display time lag because the carrier and rider are approximated as rigid bodies and m_2 is united with m_1. So when $\ddot{z}_1 \simeq -g$, we will have at the same time $\ddot{z}_2 \simeq -g$.

Then we propose a new model that has the elasticity between m_1 and m_2 in Fig. 13-(b). Human has a elasticity in the whole body joints and whole body skin and muscle. We propose to model this as an elastic force between the carrier and the rider. We correct the motion equations as follows:

$$m_1\ddot{z}_1 = N_1 - k\varepsilon - m_1 g \tag{3}$$

$$m_2\ddot{z}_2 = k\varepsilon - m_2 g \tag{4}$$

Where k is elastic coefficient and ε is a strain. The inertia force added from m_1 is delayed by the elastic force that may behave as second-lag system. The existence of time lag between m_1 and m_2 is displayed. We believe that humans effectively use this aspect of the human body.

B. Simulation

This subsection demonstrates the repositioning motion generated based on this model using a dynamics simulator.

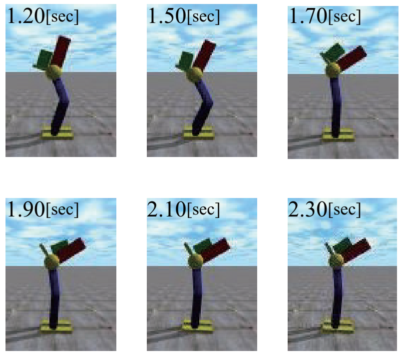

Fig. 14. The snapshots of the repositioning motion in the dynamical simulator.

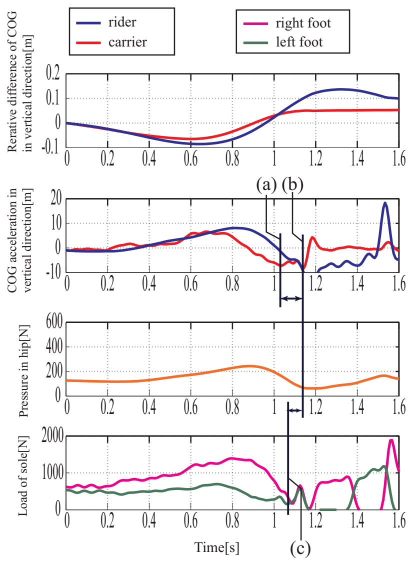

Fig. 15. The trajectories of COG, acceleration, pressure of waist and each foot in the dynamical simulator. First row: the position of COG, second row: the acceleration of COG, the third row: the pressure of upper waist and lower waist and forth row: the pressure of each foot. (a): the acceleration of carrier is -9.81[m/s^2], (b): the acceleration of rider is -9.81[m/s^2] and (c): the pressure of each foot decreases.

The parameters of the carrier and rider are $m_1 = 68.5$[kg], $m_2 = 58.0$[kg], body height of carrier is 1.685[m], and the elastic coefficient is $k = 1440$. The COG trajectories were obtained by fitting spline curves to the real data. Moreover, the upper body rotation component of the motion is based on the knacks described in the section III.

The result of simulation is shown in Fig. 14, the trajectory of COG, acceleration, pressure of hip and pressure of each foot are shown in Fig. 15.

The rider is thrown from 1.70[sec] to 1.90[sec], and the relative displacement is changed significantly as shown in Fig. 14 , the COG of rider increases by 0.1[m] in first row of Fig. 15. The acceleration of carrier reaches 9.81[m/s^2] at about $t = 1.02$[sec] in Fig. 15-(a), and the acceleration of the rider reaches 9.81[m/s^2] at about $t = 1.11$[sec] in the Fig. 15-(b). This confirms the time lag of acceleration between the carrier and the rider. After this motion the pressure at the hip and on each foot decreases, an effect similar to the one shown in Fig. 11. This shows the effectiveness of the elasticity based model.

VI. CONCLUSION

We have experimentally studied human piggyback motion, with special attention given to the repositioning motion. In the first experiment, we discussed about the knacks that are helpful in achieving the goal of the repositioning motion. These knacks are to launch the rider up by the hip and bend forward to catch the rider. In the second experiment, the effectiveness of these knacks was confirmed, and we found the principle of the repositioning motion. Moreover, we found that by using this method the carrier can hold the rider easily. Finally, to explain the time lag of acceleration, we proposed a model of the rider-carrier system that includes an elastic term between the two bodies. The validity of this model was demonstrated using a dynamical simulator.

However, we have not yet implemented this piggyback motion using a humanoid robot that is capable of generating the repositioning motion. We looked various strategies of the piggyback motion, but we have not yet analyzed them.

Therefore, our future work is to analyze the various strategies in piggyback motion, including tactile sensing patterns, and propose a whole body contact control method for piggyback motion. Then we will implement piggyback motion for transporting humans using a real humanoid robot.

VII. ACKNOWLEDGMENTS

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