A human fetus development simulation: Self-organization of behaviors through tactile sensation

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***Abstract*—Recent progresses of ultrasound imaging technology have led observations of fetal intrauterine behavior and a perspective of intrauterine learning. Understanding fetal behavior in uterus is important for medical cares for prenatal infants, because the intervention like "nesting" or "swaddling" in NICU (Neonatal Intensive Care Unit) is based on a perspective of intrauterine learning. However, fetal behavior is not explained sufficiently by the perspective. In this study, we have proposed a hypothesis in which two fetal behaviors, Isolated leg/arm movements and hand and face contact, emerge within self-organization of interaction among an uterine environment, a fetal body, and a nervous system. through tactile sensation in uterus. We have conducted computer experiments with a simple musculoskeletal model in uterus and a whole body fetal musculoskeletal model with tactile for the hypothesis. We confirmed that tactile sensation induces motions in the experiments of the simple model, and the fetal model with human like tactile distribution have behaved with the two motions similar to real fetal behaviors. Our experiments indicated that fetal intrauterine learning is possibly core concept for the fetal motor development.**

I. Introduction

Fetal behaviors, including feet stepping, hands touching her own face, and so on, remind us of neonate behaviors. Recently we has observed fetal behaviors in detail by novel devices such as a ultrasonic tomography, whereas it has been noticed since ancient times [13]. Although we have expected from the observation that behaviors in uterus are training and learning for the development after birth, we still have not understood the meaning and the mechanism of the emergence of fetal behaviors. So understanding fetal experiments in uterus is important to understand the development neonates including preterm infants.

It is confirmed that fetuses actually feel sense of vision, sound, taste, and tactile[3]. However vision is not clear for them because of the insufficient light condition in uterus. They actually respond to sound and taste, however the environment around the fetuses hardly respond to fetal movements immediately. Therefore it is reasonable that tactile is dominant for fetal sensorimotor experience because the only tactile is directory respond to fetal movement in uterus. So we consider that fetuses can learn the tactile-motor contingency and fetal behaviors would emerge from the learning in uterus.

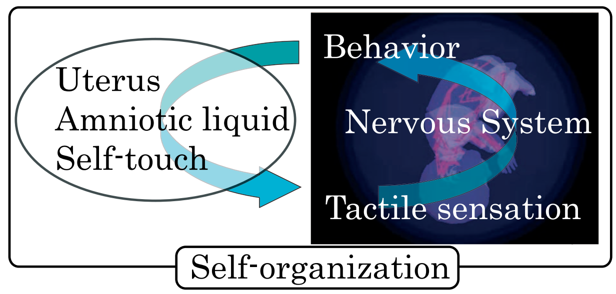

Fig. 1. Interaction between fetus and uterus.

In this paper, we propose a mechanism for emergence of two fetal behaviors from interaction among an uterine environment, a fetal body and a nervous system. The proposed mechanism is based on a spinal connectivity which is self-organized through tactile sensation. We developed computer simulation models to investigate the fetal motor development which is induced from tactile sensation. From a result of our simulation, we indicate that the fetal motor behaviors are not directly genetic, but are induced from an interaction among environment, body and nervous system. We argue that genetic determination is not behavioral patterning, but is physical structures of a nervous system and a body.

In Section II, we review development of preterm infant, developmental care, fetal sensory and motor development in uterus, and a dynamical system view for human development. Based on the review, we reinterpret fetal development perspective of a dynamical approach, and hypothesize a developmental scenario in which fetal motor activity differentiate to specific behaviors in uterus. In Section III, we introduce our computer simulation model for research of fetal sensorimotor development, and how to use it to investigate the hypothesis. In Section IV, we show the experimental setups and results. In Section V we discuss the results and conclude this research.

II. Fetal motor development in uterus

In this section, we review backgrounds of fetal sensory and motor development and Dynamical systems theory. Finally, we indicate an issue of fetal motor developmental mechanisms

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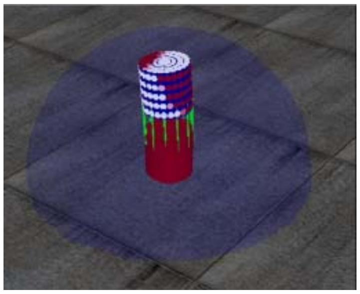

Fig. 2. One joint model with 12 muscles in simple membrane model and fluid.

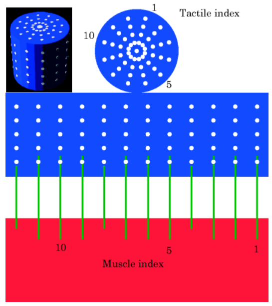

Fig. 3. One joint model with uniform tactile distribution.

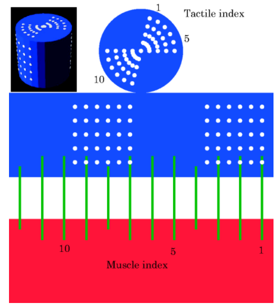

Fig. 4. One joint model with uneven tactile distribution.

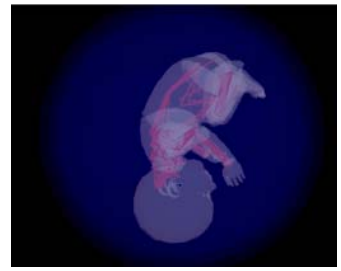

Fig. 5. Fetal muscloskeletal model. Strings in the body represent muscles. Number of muscle is 198. The fetal nabel is hanged on the center of the uterus by a ball joint.

and hypothesize the issue from a perspective of Dynamical systems view.

A. background

Ex-preterm infants generally acquire low scores for some cognitive test even if they had low risk at birth [4]. Medical doctors have been interested in fetal learning in uterus, because they consider that the learning as if infants grow in uterus would improve infants' motor and cognitive functionality.

Recently, some techniques called as Developmental Care (DC) are applied to preterm infants. "Nesting" [17] and "Swaddling" [22]. are example of DC, in which infants are folded in blankets or sheets. DC is used for preterm and term infants to be cradled and expect to facilitate infants' development. However, evidences and theoretical models that DC improves infants' development are not sufficiant.

Features of fetuses are different from features of infants, such as circulatory, respiratory and nutritionally functionality, physical environment and so on. Particularly, fetal physical environment in uterus is more constrained than infant's environment outside uterus. In uterus, fetal sensorimotor experiences are mainly somatic and fetal tactile sensory information is completely different from infant's.

Fetal tactile in physical uterine environment is separated to following three properties.

- **Amniotic fluid**: Pressure from fluid. It generates continuous stimuli and correlates to fetal movements every time.
- **Uterine wall**: Pressure form elastic- membrane. It provides pressure from outside to inside, and constrains fetal body movement.
- **Self-contacts**: Contacts between body parts. They require cooperative movements of limbs and a head.

Fetal tactile receptors are investigated in physiological and behavioral aspects [3].

From physiological observation, at 8 weeks, nerve fibers in the face, the shoulders, the axilla and the thigh have approached close to the epithelium. By 12th weeks, nerve cells have appeared on the basement in the face and the limbs.

On the other hand, behavioral experiments were conducted to observe fetal responses to tactile stimuli. Until 7th weeks, fetus does not respond to a light tactile stimuli by a horsehair. At 7 th weeks, the tactile stimuli against fetal mouth induce the mouth movements. By 11th weeks, stactile ensitive body areas expand to all of the limbs and the face.

Tactile cells on fetal skin are critical for tactile experience. At 18 weeks, Merkel cells can be differentiated in whole body, and the distribution density decrease gradually, The density varies depending on the body parts, but detailed density is not known in fetal whole body [2]. One of measures of adult tactile sensitivity is Two-Point Discrimination (TPD) from a psychophysical experiment for human tactile perception and the sensitivity and the cell distribution are correlated to TPD.

There are many research papers about fetal memory and learning [9], [10]. Particularly, sound and taste memory is frequently tested and confirmed. James[10] simply defined "learning" for studies of fetuses as "change in behaviour that occurs as a result of experience." In this paper, we use the term learning as only the sense. In this sense, there is no reason that fetuses do not learn behaviors in uterus.

De Vries et al.[6] observed and categorized fetal behaviors to 16 categories including following movements.

- **General Movements (GMs)**: The movements have no distinctive patterning or sequencing of the body parts which can be recognized. It is spontaneous **smooth** movement observed from 8 or 10 menstrual weeks, but not reflective against external stimuli.
- **Isolated Arm/Leg Movement (IALM)**: The movements is **jerky** and independent from any other body parts starting from around 10 menstrual week. They occur isolated or repeatedly in about 4 [Hz].
- **Hand/Face Contact (HFC)**: The movements is that hands touch face slowly. They occur isolated or parts of GMs after about 11 weeks.

The order of first appearing periods of the three movement categories is very suggestive. It looks that GMs induce other behavior through experience in uterus.

Thelen and Smith [21] argued that human cognitive and motor development should be explained as dynamical systems. The statement is that the development is not a preprogrammed process but is a process within an interaction among nervous system, body and surrounding environments.

By 6th to 7th gestational weeks, fetal spinal cord and medulla oblongata emerge [11]. fetal neocortex does not reach to spinal cord until 16 weeks. Spontaneous fetal behaviors

TABLE I
MASS [GRAM] OF EACH BODY SEGMENT FOR FETAL MODEL AT 20 GESTATIONAL WEEKS.

All	head	neck	chest	stomach	hip	shoulder	upper arm	forearm	hand	thigh	thin	foot
1143	302	17	204	279	95	25	21	10	3	38	19	7

are generated by neural oscillators (NOs) in spinal cord and medulla oblongata system bacause anencephalic infants (who does not have neocortex) demonstrate respiration, sleeping, waking, leg-kicking, rudimentary smiling, and even rapid eye movements while sleeping, as with healthy infants.

Generally, considering "learning", we should take into account quality of sensory input into the learning agent [18]. In this research, following aspects are important to consider the quality.

- **Environment**: Pressure features in uterus (amniotic fluid, uterine wall and self-contacts).
- **Tactile receptors**: Distribution density, sensitivity, response property

From these perspectives, uneven human tactile distribution should affect the fetal tactile experiences and emergence of behaviors.

B. *Hypothesis of fetal motor development*

1) The hypothesis: Human-like tactile distribution induces human-like motor development in uterus. We focus on the above three behaviors, GMs, IALM and HFC. The detail is as follows.

- Exploration of body and environmental dynamics by GMs: GMs, which are smooth unspecified movements, arise from NOs in fetal medulla oblongata and spinal cord system.
- Differentiation of behavior from GMs: The movements expose sensorimotor structure as correlation between tactile signal and motor output. Hebbian learning strengthen connectivity from a tactile cell to corresponding motor neurons, then reflexive behaviors emerge as counter movements against pressure from environment.
- Emergence of IALM: Counter behaviors against uterine wall emerge. The movements accelerate by a positive feedback loop motor and tactile against amniotic fluid, then movements become jerky.
- Emergence of HFC: Tactiles from self-contacts exert responsible motor neurons, then the postures are maintaind because the two body parts which are contacted push and balanced each other.

We consider that the behaviors emerge along with increasing fetal experiences, even though the nervous system has only simple connectivity.

2) Computer simulation: We used computer simulation experiments to investigate computational plausibility of the hypothesis. The simulation results is analyzed from following aspects.

- Difference in the behavior between different distribution.
- Change from smooth unspecified movement to specified movement (IALM).
- Emergence of hand and face contacts (HFC).

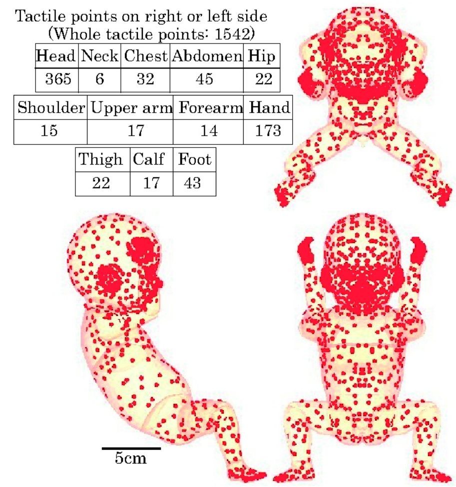

Fig. 6. Fetus tactile points allocation depending on two-point discrimination.

III. COMPUTER SIMULATION MODEL FOR FETAL MOTOR DEVELOPMENT

In this section, we show our computer simulation models.

We developed a free formed fetal body model, an uterine model and a mechanoreceptor model. The physical simulation is based on Open Dynamics Engine [19].

A. *Musculoskeletal models with tactile sensor*

We developed two muscloskeletal models to investigate our hypothesis. Muscle in the simulation is modeled based on He et al[8]. The model generates force and sensory signal of muscle spindle and muscle tendon. The spindle signal increases when corresponding muscle expands and the tendon signal increase when corresponding muscle tension increases.

1) Simple model: We developed two simple musculoskeletal model for experiments to investigate basic behaviors of the nervous system model. The models has 12 muscles and 109 tactile sensors. One of the models has tactile sensors with an uniform distribution (Fig. 3). the other one has tactile sensors with an uneven distribution (Fig. 4).

2) Fetal model: We developed two fetal musculoskeletal models which have 198 muscles and free form body morphology by triangle meshes. Muscle configurations are based on Kuniyoshi and Sangawa [14]. Body segments of the models are made from rigid body segments and the same body configuration. the models are regarded as about 20 menstrual weeks.

The two models have different tactile distribution pattern to compare the two tactile conditions. One of the models has 1542 tactile sensors which are distributed proportional to TPD [20] (Fig. 6). Another one has 448 tactiles with uniform distribution.

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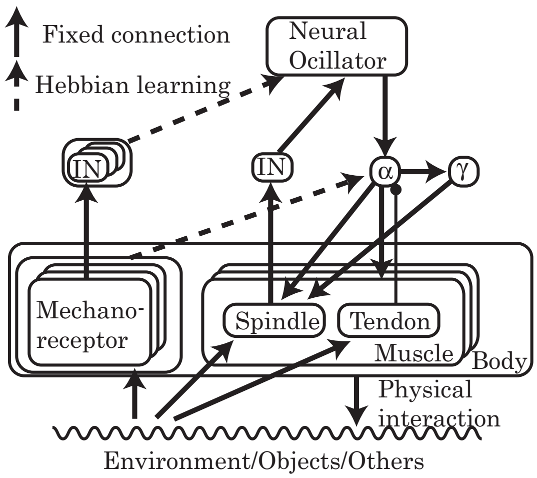


Fig. 7. Nervous system model with tactile. IN: interneuron. α: alpha motor neuron. γ: gamma motor neuron.

TABLE II

NEURAL OSCILLATOR PARAMETERS

τ	δ	ϵ	a	b	c	I_{tonic}
0.3 [sec]	0.013	0.022	0.7	0.675	1.75	0.6

TABLE III

NERVOUS SYSTEM PARAMETERS FOR THE SIMPLE MODELS.

G_α	G_{NO}	D_α	D_{NO}	η	T
0.1	0.1	10 [msec]	50 [msec]	0.001	10 [sec]

TABLE IV

NERVOUS SYSTEM PARAMETERS FOR THE FETAL MODELS.

G_α	G_{NO}	D_α	D_{NO}	η	T
0.04	0.02	10 [msec]	50 [msec]	0.05	10 [sec]

B. Uterine and contact model

Uterine model consists of three components (amniotic fluid, uterine wall and self-contact) mentioned in Section II-A. So we modeled the components.

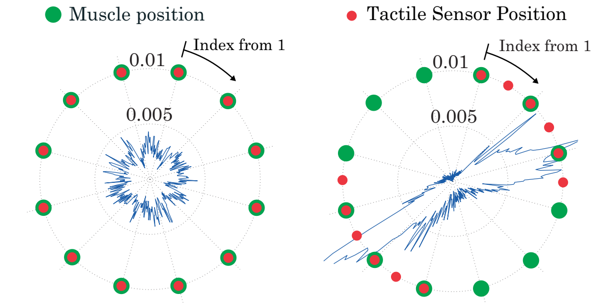
We implemented amniotic fluid as inertial resistance and a uterine wall as viscoelastic membrane which is simply modeled as linear spring. Self-contact is calculated from contact force derived from the physical simulation engine.

C. Mechanoreceptor model

Calculated pressure on a tactile point is provided to corresponding mechanoreceptor. There are four kinds of mechanoreceptors in human skin. We modeled only Merkel cells because the cells mainly detect pressure and the others detect vibratory signals. We adopted Merkel cell model as low pass filter which has cut-off frequency 50 [Hz], according to Maeno et al [16].

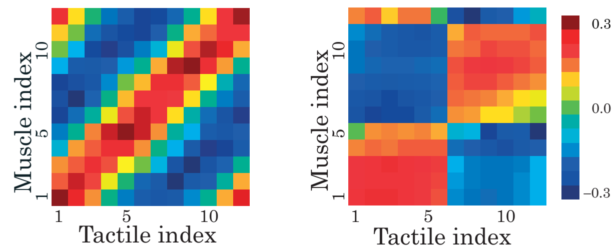
D. Nervous system model

Our model is shown in Fig. 7. As noticed in Section II-A, higher level nervous system such as neocortex does not connect to low level nervous system such as medulla oblongata or spinal cord at very early fetal period. So we have adopted only a low level nervous system model based on Kuniyoshi and Sangawa [14]. The model may explain fetal and infant's exploratory behaviors based on the chaos theory [12], [15].



(a) Uniform tactile distribution (b) Uneven tactile distribution

Fig. 8. Probability distribution of the upper link direction from top view between 9000 [sec] and 10000 [sec]



(a) Uniform tactile distribution (b) Uneven tactile distribution

Fig. 9. Connectivity from tactile to NO after 10000 [sec] learning. Positive values mean excitably connections and negative values mean inhibitory connections

The NO is modeled as BVP type equations [1].

$$\begin{aligned} y_{NO} &= 0.25v + 0.34 \\ \tau\frac{dv}{dt} &= c(v - \frac{v^3}{3} - u + I_{tonic} + G_{NO}I_{tactile}) \\ & \quad +\delta(I_{muscle} - v) \\ \tau\frac{du}{dt} &= \frac{1}{c}(v - bu + a) + \epsilon I_{muscle} \\ I_{muscle} &= -40y_{muscle} + 20 \end{aligned} \tag{1}$$

Where y_{NO} represents output of NO, y_{muscle} represents output of interneuron (IN) receiving a muscle spindle output, $I_{tactile}$ represents input from whole tactile signals integrated by weight. Neuron model parameters are same as Kuniyoshi and Sangawa [14] shown in Table II.

Outputs of modeled neurons is limited between $0-1$ corresponding to spike ratio.

In this research, we added connectivity from tactile cells to motor neurons but eliminated integrative connectives from muscles to motor neurons because we want to observe pure effects from tactile sensation to motor activity.

Tactile information transfer to α motor neurons and NOs. α motor neurons receive the information from Merkel cells directly. NOs receive the information via IN.

Input $\boldsymbol{I}_{tactile} = [I_{tactile,i}, \cdots, I_{tactile,M}]^T$ to α motor neurons or NO is described as follows.

$$\boldsymbol{I}_{tactile} = \boldsymbol{W}\boldsymbol{x} \tag{2}$$

$\boldsymbol{x} = [x_i, \cdots, x_N]^T$ is output vector of Merkel cells or INs, $W = [\boldsymbol{w}_1, \cdots, \boldsymbol{w}_i, \cdots, \boldsymbol{w}_M]^T$, $\boldsymbol{w}_i = [w_{i1}, \cdots, w_{ij}, \cdots, w_{iN}]^T$ is weight of connectivity. Each connection has conduction delay D.

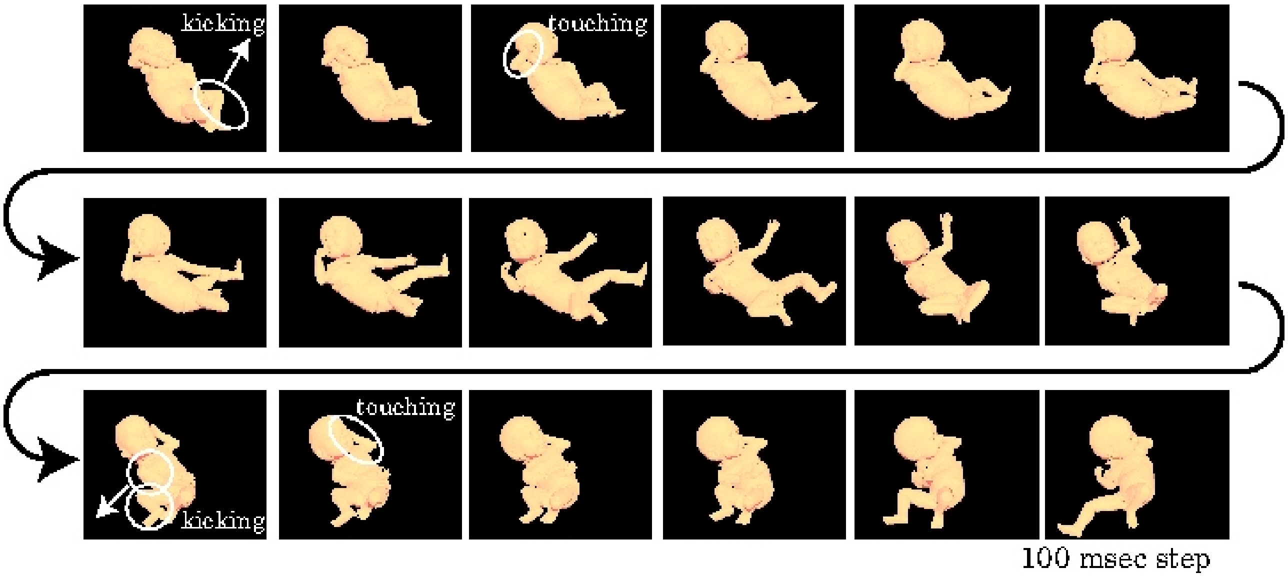


Fig. 10. An fetal with TPD tactile distribution moves arms and legs jerky. The motions look isolated arm movement.

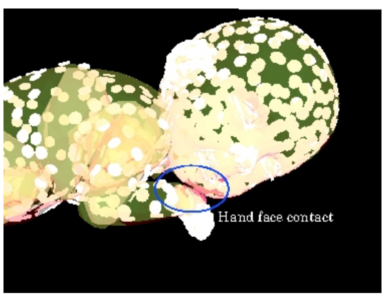


Fig. 11. An example of hand face contacts. Each circle represents tactile point. Red color represents outputs of mechanoreceptors corresponding to tactile points. The body is transparent.

Connectivity $\boldsymbol{W}$ from tactile cells to spinal cells are learned by Covariance rule [5], which is modified from Hebb rule.

$$\frac{d\boldsymbol{W}}{dt} = \eta\left(\boldsymbol{y} - \bar{\boldsymbol{y}}\right)\left(\boldsymbol{x} - \bar{\boldsymbol{x}}\right)^T \tag{3}$$

where $\boldsymbol{y} = [y_1, \cdots, y_M]^T$ is output vector of the motor neurons, $\bar{\boldsymbol{x}}, \bar{\boldsymbol{y}}$ are averages of $\boldsymbol{x}, \boldsymbol{y}$ for previous T[sec]. $\boldsymbol{w}_i$ is normalized as follows.

$$\boldsymbol{w}_i \leftarrow \frac{\boldsymbol{w}_i}{\|\boldsymbol{w}_i\|} \tag{4}$$

Above learning rule is applied separatly to connection between INs and NOs or to connection between mechanoreceptors and α motor neurons.

Each simulation starts with $\boldsymbol{w}$ randomized with uniform distribution.

IV. Simulation experiment

A. Simple muscloskeletal model

We conducted computer simulations with uneven and uniform tactile distribution models. Parameters used in the simulations are shown in Table III.

Fig. 8(a) and Fig. 8(b) represent probability distributions of direction of the upper body from the top view between 9000 [sec] and 10000 [sec]. The distributions indicate that different tactile distributions result in different behaviors through the neural model.

We have considered that the different biases of the tactile distributions induce different nervous connectivity, then the different behavioral tendencies arise.

Fig. 9(a) and Fig. 9(b) are connectivity map from INs (tactile points on the top row of upper body) NOs after 10000 [sec] learning. The maps indicate that reciprocal connectivity emerge to the antagonistic muscles.

B. Fetal model

1) Qualitative aspect: In the beginning of the simulation, both each simulated fetus moves a trunk, a head, and limbs smoothly.

The movements of fetal model with TPD tactile distribution change to fast and jerky (Fig. 10). After 3000 [sec] simulation, fetal hand frequently touch its own face like Fig. 11.

In contrast, behaviors of simulated fetus with uniform tactile distribution actually change with simulation time, but not significant as well as the other one.

2) Quantitative aspect: We measured jerk of limbs to observe change of movements from GMs to IALM. Jerk is derivative of acceleration and the index for smoothness indicating that muscle forces change [7]. The averages of $\|d^3\boldsymbol{p}/dt^3\|$ for 100 [sec] for the limbs are shown in Fig. 13 and Fig. 13. Increasing the index implys that the positive feedback through tactile arise as mentioned in Section II-B1.

For a fetal model with TPD tactile distribution, Jerk for each limb increase quiker than uniform tactile distribution.

In terms of HFC, we calculated ratio of duration while hands contact its own face. The ratios of contact are shown in Fig. 15 and Fig. 14 For right hand of fetal model with TPD tactile distribution, the ratio significantly increase.

V. Conclusion

In this paper, we conducted experiments to simulate emergence of fetal behaviors. We have confirmed that 2 types

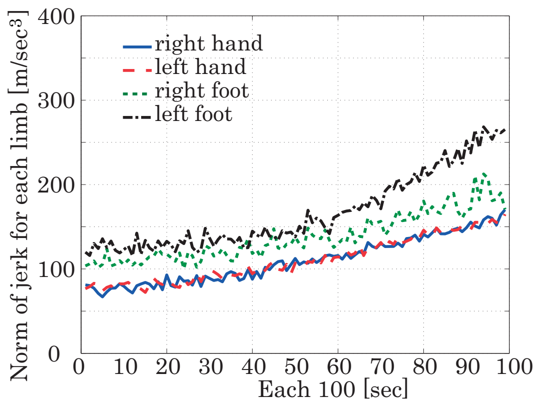


Fig. 12. Jerk of fetal model limbs with the uniform tactile distribution.

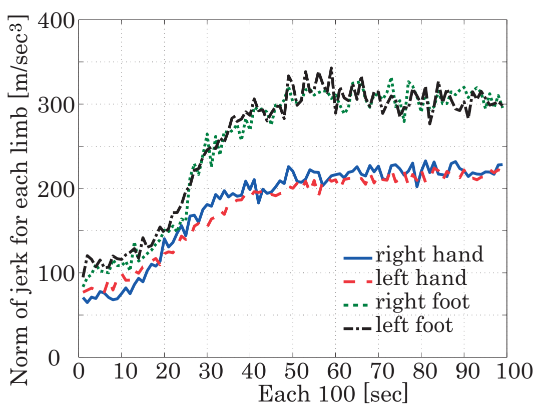


Fig. 13. Jerk of fetal model limbs with the TPD tactile distribution.

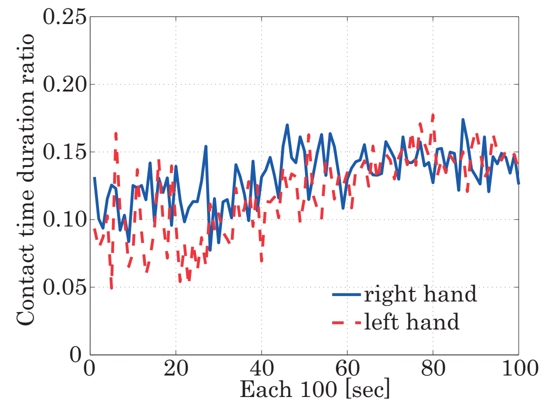


Fig. 14. Hand and face contacts with the uniform tactile distribution.

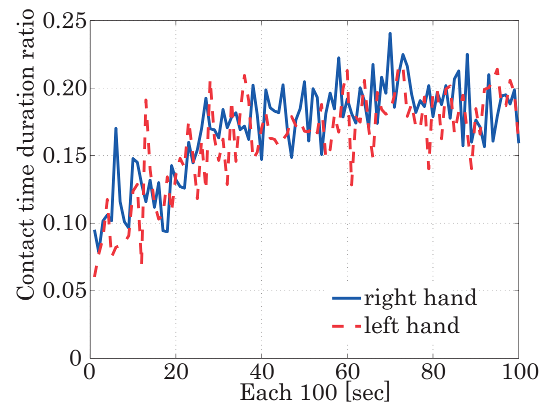


Fig. 15. Hand and face contacts with the TPD tactile distribution.

of behavors (IALM and HFC) emerge from GMs and the behaviors are strongly affected from tactile distribution.

Our future work is comparison between our model and actual fetal behaviors, higher level nervous system model for more complex behavior such as limbs cordination or infant behavior such as hand regard, croling, rolling over and so on.

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