OPTIMIZING SIMULATION FOR LONG DISTANCE THROW IN BASEBALL ACCORDING TO AN ORDER OF PLURAL OBJECTIVES IN PRACTICE

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Abstract. *We describe the simulation method for generating an ideal motion of an upper limb for long distance throw in baseball by an optimizing calculation. We also report the simulation experiment by using the method when the importance among plural objectives is dynamically changed in the improving process according to an order. When the consequence of simulation experiments is applied to an actual human, it is significant to consider not only the importance of objectives, but also the order of the importance when we make a practice for improving a motion.*

1. Introduction

When a person learns a motion with plural objectives, the person will make a practice so that each objective is satisfied one by one according to an adequate order because it is difficult to satisfy all objectives at the same time. In the situation, it may happen that the satisfied objective is broken when the objective is changed to another. It may also happen that the consequent motions are different each other with depending on the order for the practice to accomplish an objective. It is interesting to simulate the improving process when a human learns a motion with plural objectives, and to investigate whether the consequent motion is converged to the different motion or not when the order of execution for the objective is changed. The purpose of the present paper is to report the simulation experiment for a motion of long distance throw in baseball when the importance among plural objectives is changed in the improving process according to an order. At first, we explain the simulation method based on an optimizing calculation reformed our previous works [1][2][3][4], and then we describe the experiment and its results.

2. Simulation Method

2.1. Process Flow

It can be considered that the proficient motion is an ideal or optimal motion, especially, in the field of sports. We call the ideal motion generated under the artificial environment like a computer "artificial proficient motion". Figure 1 shows the process flow until generating the optimizing motion of long distance throw in the specified velocity and the specified angle at throwing a ball. At first, the motion of making a long throw by an actual player is captured by DLT (Direct Linear Transformation) method [5]. The captured data is transformed to the time sequence data of joint angles. The inertia tensor of each segment of an upper limb and a ball are calculated by numerical integration with approximated curved surfaces. The time sequence data of joint angles, their inertia tensors, the specified ball velocity, and the specified angle at the ball release are input to the process of executing the optimization. After the optimizing calculation, the optimal throwing motion is combined with the original motion for other segments of the body except the upper limb, and then the combined motion for the whole human body is visualized by the browsing software that we have developed. The numerical data for the optimal throwing motion is also represented by a graph for analysis.

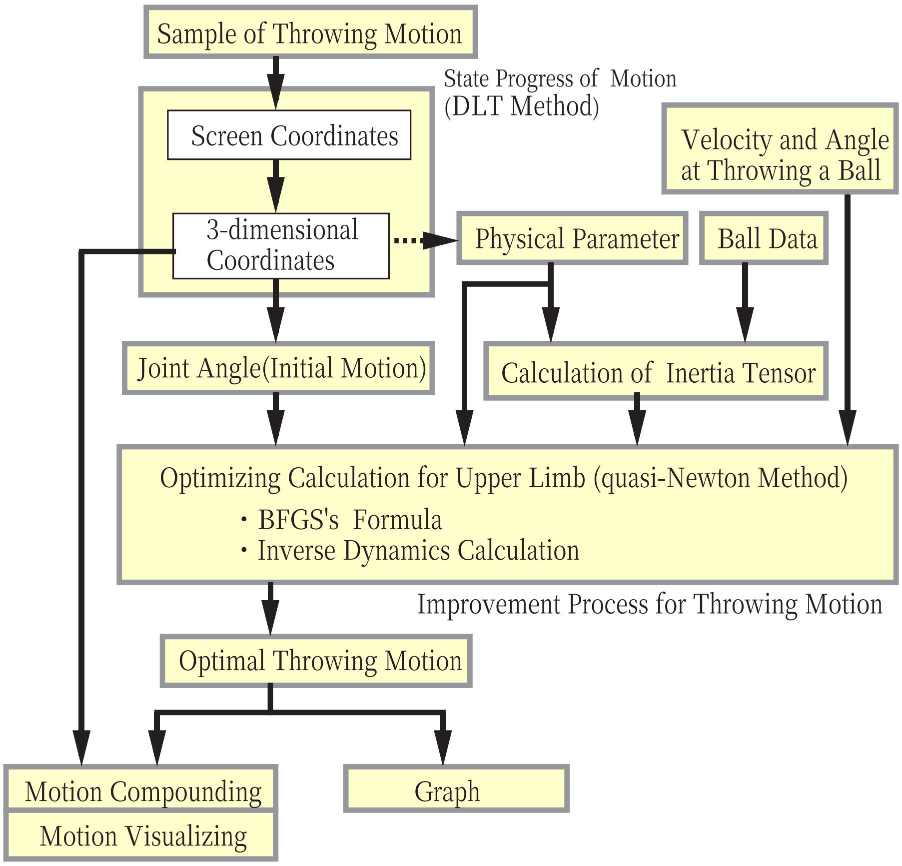


Figure 1 Process Flow

2.2 Mathematical Model

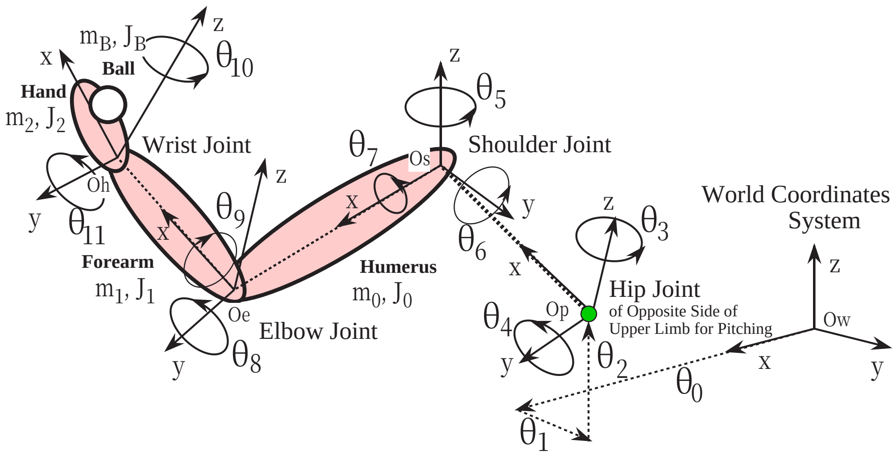


Figure 2 Mathematical Model of Upper Limb

Figure 2 illustrates our 3-dimensional mathematical model for an upper limb in the simulation, and which consists of 4 segments, a humerus, a forearm, a hand, and a ball. The model totally has twelve degrees of freedom. The motion of an upper limb is only affected from the trajectory of the shoulder joint, and the five degrees of freedom is assigned to the control for the trajectory. The remaining seven degrees of freedom is assigned to the upper limb according to an actual human. D-H (Denavit and Hartenberg) representation [6] is applied to the local coordinate system for the model, where the x-axis of it coincides with the longitudinal axis of the segment.

The model is described by two systems of Lagrange equations that express the motion of long distance throw before/ after releasing a ball. For example, the system of Lagrange equations before releasing a ball can be represented by the following equations (1), (2), and (3):

$$
\begin{aligned}
\tau_i =\; & \sum_{k=0}^{7} \mathrm{trace}\left[\frac{\partial T_7}{\partial \theta_k} J_0 \frac{\partial T_7^T}{\partial \theta_i}\right]\ddot{\theta}_k + \sum_{k=0}^{9} \mathrm{trace}\left[\frac{\partial T_9}{\partial \theta_k} J_1 \frac{\partial T_9^T}{\partial \theta_i}\right]\ddot{\theta}_k \\
& + \sum_{k=0}^{11}\left[\mathrm{trace}\left[\frac{\partial T_{11}}{\partial \theta_k} J_2 \frac{\partial T_{11}^T}{\partial \theta_i}\right] + \mathrm{trace}\left[\frac{\partial T_B}{\partial \theta_k} J_B \frac{\partial T_B^T}{\partial \theta_i}\right]\right]\ddot{\theta}_k \\
& + \sum_{k=0}^{7}\sum_{l=0}^{7} \mathrm{trace}\left[\frac{\partial^2 T_7}{\partial \theta_l \partial \theta_k} J_0 \frac{\partial T_7^T}{\partial \theta_i}\right]\dot{\theta}_k \dot{\theta}_l + \sum_{k=0}^{9}\sum_{l=0}^{9} \mathrm{trace}\left[\frac{\partial^2 T_9}{\partial \theta_l \partial \theta_k} J_1 \frac{\partial T_9^T}{\partial \theta_i}\right]\dot{\theta}_k \dot{\theta}_l \\
& + \sum_{k=0}^{11}\sum_{l=0}^{11}\left[\mathrm{trace}\left[\frac{\partial^2 T_{11}}{\partial \theta_l \partial \theta_k} J_2 \frac{\partial T_{11}^T}{\partial \theta_i}\right] + \mathrm{trace}\left[\frac{\partial^2 T_B}{\partial \theta_l \partial \theta_k} J_B \frac{\partial T_B^T}{\partial \theta_i}\right]\right]\dot{\theta}_k \dot{\theta}_l \\
& - m_0 g^T \frac{\partial T_7}{\partial \theta_i} r_0 - m_1 g^T \frac{\partial T_9}{\partial \theta_i} r_1 - m_2 g^T \frac{\partial T_{11}}{\partial \theta_i} r_2 - m_B g^T \frac{\partial T_B}{\partial \theta_i} r_B
\end{aligned}
$$

whre $i=0,1,\cdot\cdot\cdot,7$ (1)

$$\tau_i = \sum_{k=0}^{9} \mathrm{trace}\left[\frac{\partial T_9}{\partial \theta_k} J_1 \frac{\partial T_9^T}{\partial \theta_i}\right]\ddot{\theta}_k$$
$$+ \sum_{k=0}^{11}\left[\mathrm{trace}\left[\frac{\partial T_{11}}{\partial \theta_k} J_2 \frac{\partial T_{11}^T}{\partial \theta_i}\right] + \mathrm{trace}\left[\frac{\partial T_B}{\partial \theta_k} J_B \frac{\partial T_B^T}{\partial \theta_i}\right]\right]\ddot{\theta}_k$$
$$+ \sum_{k=0}^{9}\sum_{l=0}^{9} \mathrm{trace}\left[\frac{\partial^2 T_9}{\partial \theta_l \partial \theta_k} J_1 \frac{\partial T_9^T}{\partial \theta_i}\right]\dot{\theta}_k \dot{\theta}_l$$
$$+ \sum_{k=0}^{11}\sum_{l=0}^{11}\left[\mathrm{trace}\left[\frac{\partial^2 T_{11}}{\partial \theta_l \partial \theta_k} J_2 \frac{\partial T_{11}^T}{\partial \theta_i}\right] + \mathrm{trace}\left[\frac{\partial^2 T_B}{\partial \theta_l \partial \theta_k} J_B \frac{\partial T_B^T}{\partial \theta_i}\right]\right]\dot{\theta}_k \dot{\theta}_l$$
$$- m_1 g^T \frac{\partial T_9}{\partial \theta_i} r_1 - m_2 g^T \frac{\partial T_{11}}{\partial \theta_i} r_2 - m_B g^T \frac{\partial T_B}{\partial \theta_i} r_B \quad \text{where } i=8,9 \tag{2}$$

$$\tau_i = \sum_{k=0}^{11}\left[\mathrm{trace}\left[\frac{\partial T_{11}}{\partial \theta_k} J_2 \frac{\partial T_{11}^T}{\partial \theta_i}\right] + \mathrm{trace}\left[\frac{\partial T_B}{\partial \theta_k} J_B \frac{\partial T_B^T}{\partial \theta_i}\right]\right]\ddot{\theta}_k$$
$$+ \sum_{k=0}^{11}\sum_{l=0}^{11}\left[\mathrm{trace}\left[\frac{\partial^2 T_{11}}{\partial \theta_l \partial \theta_k} J_2 \frac{\partial T_{11}^T}{\partial \theta_i}\right] + \mathrm{trace}\left[\frac{\partial^2 T_B}{\partial \theta_l \partial \theta_k} J_B \frac{\partial T_B^T}{\partial \theta_i}\right]\right]\dot{\theta}_k \dot{\theta}_l$$
$$- m_2 g^T \frac{\partial T_{11}}{\partial \theta_i} r_2 - m_B g^T \frac{\partial T_B}{\partial \theta_i} r_B \quad \text{where } i=10,11 \tag{3}$$

In these equations, mi is the mass, Ji is the matrix of the inertia, ri is the position vector of the barycenter, g is the vector of the gravitational acceleration, and Ti=A0A1・・・Ai where Ai is the 4 times 4 matrix that transforms the expression on the i-th local coordinate system to the expression on the i-1-th local coordinate system and AB is the matrix that transforms the expression on the local coordinate system for the ball to the expression on the 11th local coordinate system. The system of Lagrange equations after releasing a ball can be represented in the same way.

In our mathematical model, we determined the release point for throwing a ball by the following estimation function Er(t) represented by the equation (4):

$$E_r(t) = 0.1\, v_b(t-2\Delta t)(1-|\tan\alpha(t-2\Delta t) - \tan\alpha_{given}|)$$
$$+ 0.2\, v_b(t-\Delta t)(1-|\tan\alpha(t-\Delta t) - \tan\alpha_{given}|)$$
$$+ 0.4\, v_b(t)(1-|\tan\alpha(t) - \tan\alpha_{given}|)$$
$$+ 0.2\, v_b(t+\Delta t)(1-|\tan\alpha(t+\Delta t) - \tan\alpha_{given}|)$$
$$0.1\, v_b(t+2\Delta t)(1-|\tan\alpha(t+2\Delta t) - \tan\alpha_{given}|) \tag{4}$$

where vb(t) is the ball velocity at time t, Δt is the length of the interval of the discrete time, $\alpha(t)$ is the angle between the ball velocity vector and the horizontal direction, and α given is the specified angle at throwing a ball. The motion of the ball after releasing is represented by Newton equation including the frictional force of air in proportion to the velocity.

2.3 Objective Function

There were many studies of planning the trajectory of the motion to reach the target point for an upper limb in biocybernetics [7][8][9]. We defined the objective function according to the necessary condition with considering the previous works in biocybernetics. The following equation (5) is the objective function that we have determined for the motion of long distance throw:

$$
\begin{aligned}
E\,(\Theta(t)) = {} & Ws_0 \int (\tau_3^2 + \tau_4^2)\,dt + Ws_1 \int (\tau_5^2 + \tau_6^2 + \tau_7^2)\,dt \\
& + Ws_2 \int (\tau_8^2 + \tau_9^2)\,dt + Ws_3 \int (\tau_{10}^2 + \tau_{11}^2)\,dt \\
& + W_0\ (\text{Penalty for Joint Movability}) \\
& + W_1\ (\text{Penalty for the Range and the Smoothness of Shoulder Trajectory}) \\
& + W_2\ (\text{Penalty for Joint Torque}) \\
& + W_3 \int [(d\tau_3/dt)^2 + (d\tau_4/dt)^2 + \cdots + (d\tau_{11}/dt)^2]dt \\
& + W_4 \int [(d^2\tau_3/dt^2)^2 + (d^2\tau_4/dt^2)^2 + \cdots + (d^2\tau_{11}/dt^2)^2]dt \\
& + W_5\ (\text{Penalty for Ball Velocity}) \\
& + W_6 \int (v_s^2 + v_e^2 + v_w^2 + v_h^2)\,dt \\
& + W_7 \int [(dv_s/dt)^2 + (dv_e/dt)^2 + (dv_w/dt)^2 + (dv_h/dt)^2 dt \\
& + W_8 \int [(d^2v_s/dt^2)^2 + (d^2v_e/dt^2)^2 + (d^2v_w/dt^2)^2 + (d^2v_h/dt^2)^2]dt \\
& + W_9\ (\text{Penalty for Angle at Throwing})
\end{aligned}
\tag{5}
$$

where $\Theta(t)=(\theta 3(t), \theta 4(t), \cdots, \theta 11(t))$, Wsi and Wi are the weight coefficients, vs is the velocity at the shoulder joint, ve is the velocity at the elbow joint, vw is the velocity at the wrist joint, and vh is the velocity at the top of the hand.

The proficient motion in the field of sports is often praised by the expression with the keywords of "wasteless" and "smooth" in general. Minimizing from the 1st term to the 4th term in the equation (5) corresponds to reducing wasteless in a motion. Minimizing the 8th and 9th term makes the motion smooth in the sense that the sudden occurrences or changes of muscular tensions exist as little and/or few as possible in the motion. The 5th and the 6th terms play a role to restrict the motion in the range of the movability for the actual human. The 7th term is the constraint for avoiding from the excessive load of torque. The 10th and the 14th terms are to accomplish the specified velocity and the specified angle at releasing a ball. It is important for avoiding from an injury to execute the smooth acceleration before throwing a ball and the smooth braking after throwing for each segment. The terms from the 11th to the 13th play a role for realizing it.

2.4 Optimization

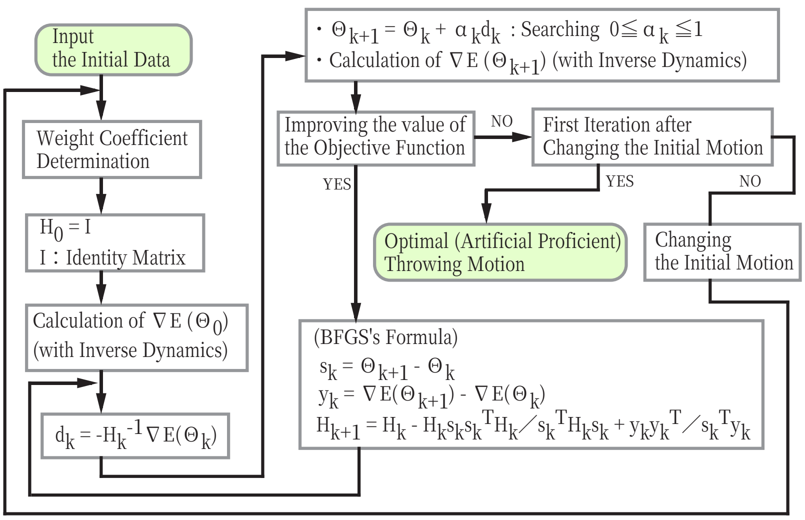


Figure 3 Optimizing Process

The optimizing process for the motion of long distance throw is executed to nine degrees of freedom in our model by a quasi-Newton method that consists of the calculation of Hessian by BFGS's formula and the calculation of the search vector. Figure 3 shows the process flow of the optimizing calculation in detail, where $E(\Theta k(t))$ is the objective function, $\Theta k(t)$ is the vector of joint angle functions in the k-th iteration, and Hk is Hessian in the k-th iteration. We developed the optimizing method with changing the weight coefficients dynamically, and we utilized the dynamic change of the weight coefficients for the simulation experiments. The weight coefficients, Wsi, are determined by the way such that calculating the value Vs0 of the 2nd term when Ws1=1 for an initial motion, and then the ratio of Vs0 to each value of the 1st term, the third term, and the fourth term is "*1: 1: 1*". After determining Wsi, the total value V0 from the 1st term to the 4th term is calculated. The weight coefficients Wi are determined by the way such that the ratio of V0 to each value from the 5th term to the 14th term is "*1: 1: 1: a: b: c: d: e: f: g*". When the optimizing process is converged, the succeeding optimizing process is executed after the initial motion is changed to the preceding converged throwing motion with renewing weight coefficients, These optimizing processes are repeated until the improvement for the value of the objective function does not happen.

3. Simulation Experiments

3.1 Method

It is possible to control the importance of objectives in improving process for the motion of long distance throw by changing weight coefficients ratio of the objective function (5). We classify the objective in the equation (5) to the condition of the angle at release, the condition of the velocity at release, and the condition of the smooth, and those can be controlled by the values from "*a*" to "*g*". According to the classification, we determined following 3 types of weight coefficients ratio.

Weight Type (1) for the condition of the angle:
$a=0.1, b=0.1, c=0.1, d=0.1, e=0.05, f=0.025,$ and $g=5.0.$
Weight Type (2) for the condition of the velocity:
$a=0.1, b=0.1, c=5.0, d=5.0, e=2.5, f=1.25,$ and $g=0.1.$
Weight Type (3) for the condition of the smooth:
$a=5.0, b=2.5, c=0.1, d=0.1, e=0.05, f=0.025,$ and $g=0.1.$

The conditions of the six kinds of orders for the optimization were illustrated in Table 1.

Table 1 Order of Execution for Weight Types

Execution Order	**1**	**2**	**3**
Condition A	*Weight Type (1)*	*Weight Type (2)*	*Weight Type (3)*
Condition B	*Weight Type (1)*	*Weight Type (3)*	*Weight Type (2)*
Condition C	*Weight Type (2)*	*Weight Type (1)*	*Weight Type (3)*
Condition D	*Weight Type (2)*	*Weight Type (3)*	*Weight Type (1)*
Condition E	*Weight Type (3)*	*Weight Type (1)*	*Weight Type (2)*
Condition F	*Weight Type (3)*	*Weight Type (2)*	*Weight Type (1)*

3.2 Conditions

Table 2 Physical Data and Ball Data

	Mass (kg)	Inertia Tensor Hxx (m^2 kg)	Inertia Tensor Hyy (m^2 kg)	Inertia Tensor Hzz (m^2 kg)	Inertia Tensor Hxy (m^2 kg)	Inertia Tensor Hyz (m^2 kg)	Inertia Tensor Hzx (m^2 kg)
Humerus	1.9347	2.2021×10^{-3}	1.2148×10^{-2}	1.2413×10^{-3}	1.8131×10^{-5}	-6.0618×10^{-6}	-4.2412×10^{-5}
Forearm	1.1280	8.0259×10^{-4}	5.7933×10^{-3}	5.9546×10^{-3}	8.3040×10^{-7}	6.4550×10^{-7}	9.3844×10^{-5}
Hand	0.3455	2.0820×10^{-4}	4.6550×10^{-4}	5.0491×10^{-4}	-1.5749×10^{-6}	-2.3634×10^{-6}	-1.1901×10^{-5}
Ball	0.1418	7.4739×10^{-5}	7.4739×10^{-5}	7.4739×10^{-5}	0.0	0.0	0.0

The simulation experiment was executed with the same initial motion that a professional baseball catcher threw a ball to the second base in an overhand style. The initial motion was constructed between the take-back phase and the follow-through phase for 0.5999 second. The simulation was carried out in about 0.0020 second for a time step in the inverse dynamics calculation. The threshold for the penalty of joint movability on an upper limb was decided from the medical data. The threshold for the penalty of the load of torques was determined that the value for a wrist joint is 10.0 Nm and the value for an elbow joint has been 50.0 Nm. The threshold for the ball velocity at the release point was determined 33.33 m/s, and the angle at the release was arranged between 40 and 45 degree. The ball release was assumed to occur between 0.3400 and 0.4199 second. Table 2 shows the physical data for an upper limb and a ball in the simulation experiment.

4. Results and Discussion

Figure 4 illustrates the original motion used for the initial motion with a ball trajectory. Figure 5 shows the consequent motions with a ball trajectory and they can be classified to three types of throwing style. The first one was a side-hand style like a discus throw in condition A and C. The second one was a overhand style like a baseball throw in condition B and D. The third one was the middle style between the first and the second in Condition E and F. Those differences among them were mainly generated from the change of joint angle $\theta 6$ in Graph 1. It can be understood that a motion converges to the different type of a motion from the improving process changed the order of the importance for plural objectives even if it begins the same initial motion. Table 3 shows the maximum velocity at each position of a joint, and the ball velocity and the angle at release in each consequent motion. The condition of angle at release was satisfied in all conditions, but the velocity at ball release was insufficient from the threshold value in all conditions. The reason for it can be considered that

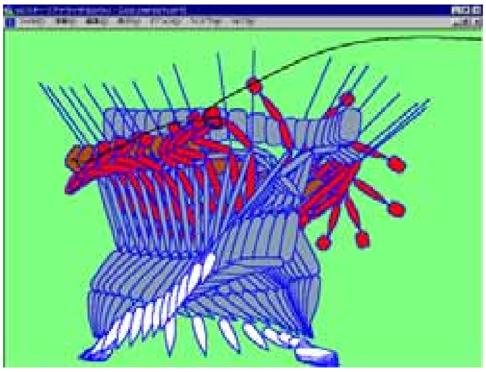


Figure 4 Original Motion

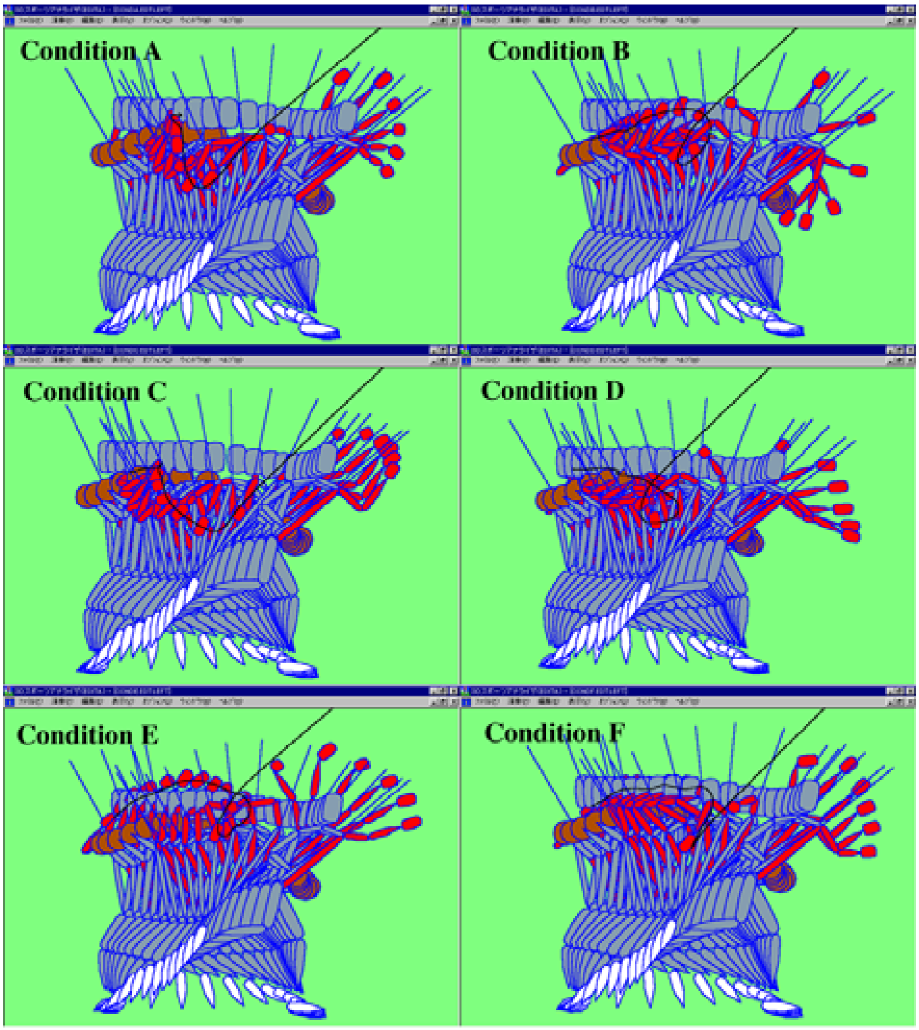
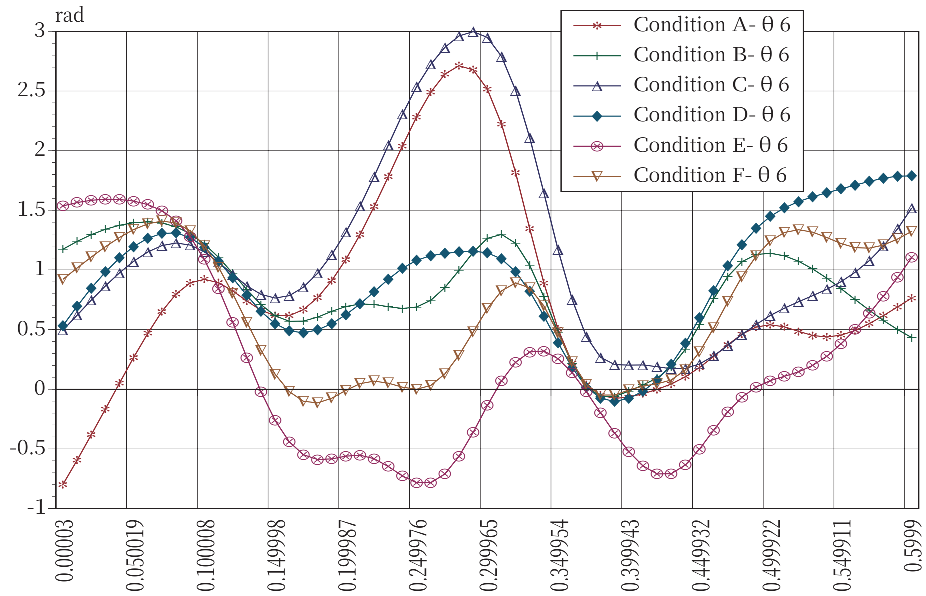


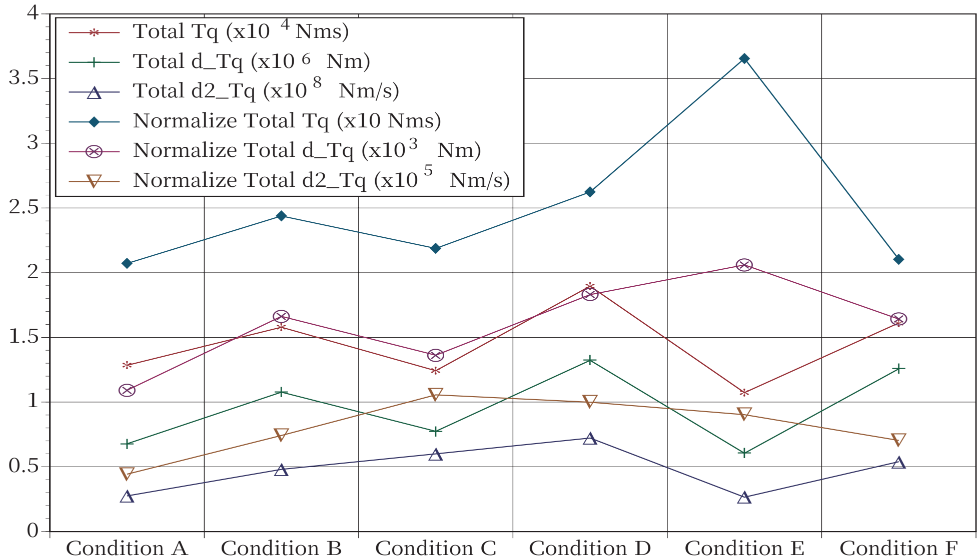
Figure 5 Consequent Motions



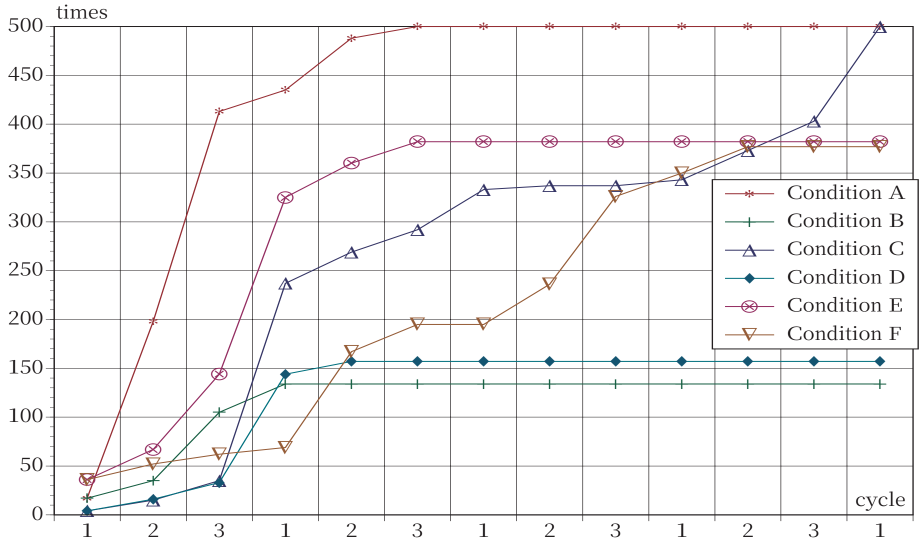
Graph 1 Joint Angle of θ 6

Table 3 Maximum Velocity and Angle at Release

	Condition A	Condition B	Condition C	Condition D	Condition E	Condition F
Shoulder (m/s)	6.63 (0.302)	6.52 (0.298)	6.33 (0.298)	6.92 (0.304)	6.77 (0.298)	6.67 (0.298)
Elbow (m/s)	9.65 (0.370)	12.59 (0.322)	8.05 (0.366)	10.54 (0.358)	6.72 (0.370)	10.16 (0.370)
Wrist (m/s)	18.01 (0.394)	19.55 (0.394)	15.59 (0.382)	18.87 (0.378)	13.38 (0.416)	18.40 (0.390)
Hand (m/s)	23.95 (0.402)	25.23 (0.400)	19.25 (0.382)	24.34 (0.384)	16.44 (0.400)	25.75 (0.388)
Ball (m/s)	24.90 (0.390)	25.45 (0.382)	23.84 (0.382)	26.88 (0.374)	17.14 (0.408)	27.68 (0.386)
Angle (degree)	40.69	42.43	42.30	40.94	40.79	42.07



Graph 2 Total Torque and Torque Derivatives



Graph 3 Converging Process

the ball velocity was compromised to the proper shortage value because there were some conditions decreasing the ball velocity in the objective function. The condition of the ball velocity will be satisfied if the conditions decreasing the velocity is removed or the weight coefficient for it is increased large value.

Graph2 indicates the total torques, the total torque derivatives, and the total torque derivatives of second degree. Normalization was executed by dividing the square value of a ball velocity in each condition. Those values were well decreased in condition A, C, and F. It can be considered that the first type of throwing style tends to decrease those values. Graph 3 shows the increase of the number of iteration in each cycle of the weight type. Complete convergence was accomplished in condition B and D, but in other conditions, the execution of the optimizing process was given up for the constraint of the calculation time. It can be seen that the consequent motion tends to be largely changed from the initial motion when the number of iteration was larger.

5. Conclusion

In the present paper, we described the simulation method for generating an ideal motion of an upper limb in long distance throw in baseball by an optimizing calculation. We also reported the simulation experiment by using the method when the importance among plural objectives is dynamically changed in the improving process according to an order. From the results of the experiment, it could be seen that the different order for the importance of the plural objectives generated the different consequent motion. If the result is applied to an actual human, the consequent motions from making a practice for improving will be different from each other with depending on the order of the importance for objectives. It is significant to consider not only the importance of objectives, but also the order of the importance when we make a practice for improving a motion.

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