An Interphalangeal Coordination-based Joint Motion Planning for Humanoid Fingers: Experimental Verification

Byoung-Ho Kim

Abstract: The purpose of this paper is to verify the practical effectiveness of an interphalangeal coordination-based joint motion planning method for humanoid finger operations. For the purpose, several experiments have been performed and comparative experimental results are shown. Through the experimental works, it is confirmed that according to the employed joint motion planning method, the joint configurations for a finger's trajectory can be planned stably or not, and consequently the actual joint torque command for controlling the finger can be made moderately or not. Finally, this paper analyzes that the interphalangeal coordination-based joint motion planning method is practically useful for implementing a stable finger manipulation. It is remarkably noted that the torque pattern by the method is well-balanced. Therefore, it is expected that the control performance of humanoid or prosthetic fingers can be enhanced by the method.

Keywords: Humanoid fingers, interphalangeal coordination, joint motion planning.

1. INTRODUCTION

Handling an object by multi-fingered hands is one of the fundamental performances of intelligent humanoid robots which are now actively developed in many research groups [1]. The dexterity of an object manipulation is basically dependent on a hand(or finger) mechanism and its control method. Thus, a lot of hand mechanisms and control algorithms have been studied [2-7]. For instance, Jacobsen, *et al.* [2] developed an interesting hand mechanism. Cutkosky [8] provided an idea for any choice in many grasp styles for an object manipulation, and Iberall [9] tried to classify the feature of human prehension to mimic the skills of human hands for dexterous robotic and prosthetic hands. Ueda, *et al.* [7] showed an effort for effective grasping by adapting sensory elements in fingertips. These efforts are being applied to develop dexterous humanoid hands. The Iberall's bio-mimetic approach, especially, is very remarkable for developing an effective control strategy of a human-like mechanism.

In fact, a humanoid hand is highly desirable to implement various human-like behaviors. It is natural for implementing such a human-like behavior that each finger should be available to mimic the motion patterns of a human finger and also effectively combined with each other for an object manipulation task. In this sense, there are some efforts to use an interphalangeal relationship in a human finger [10-12]. Hahn, *et al.* [10] reported the flexion and extension ranges of the index finger in many persons. Kamper, *et al.* [11] observed the fingertip trajectories during grasp. Kim [12] also checked the interphalangeal motions of human fingers through iterative grasping operations. Thus it is certainly pointed out that the quality between DIP and PIP joints of fingers except thumb is approximately linear. Recently, this concept has been applied to make an interphalangeal coordination-based joint motion planning method [13]. There are two major contributions. One is to specify an empirical model that identifies effectively the interphalangeal coordination of a humanoid finger with 3 degrees of freedom in planar space. The other is to incorporate the coordination factor into planning successive joint configurations. Consequently, he addressed that a human-like finger motion can be implemented by employing the joint motion planning method. It is a somewhat interesting point for humanoid researchers to think about human-like motions. However, the effectiveness of the method was shown roughly by simulation study. So, more intensive practical demonstration is still required for reliable robotic applications.

Thus, the objective of the current paper is to demonstrate the practical effectiveness of the interphalangeal coordination-based joint motion planning method for applications to humanoid fingers. For the purpose of experimental verification, two joint

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Byoung-Ho Kim is with the Division of Electrical and Mechatronics Engineering, Kyungsung University, 314-79 Daeyeon 3-dong, Nam-gu, Busan 608-736, Korea (e-mail: kimbh@ks.ac.kr).

motion planning methods are represented briefly in Section 2. Several experimental works are implemented, and significant results are analyzed in Section 3. Finally, concluding remarks are summarized in Section 4.

2. JOINT MOTION PLANNING METHODS: MJP AND ICJP

This section briefly reveals the conventional manipulability-based joint motion planning method (MJP) and the interphalangeal coordination-based joint motion planning method (ICJP) presented in [13] for the purpose of their comparative experimental verifications.

2.1. MJP

The primitive joints for the planar motion of the index finger are represented by MCP (MetaCarpoPh alangeal), PIP (Proximal Inter Phalangeal), and DIP (Distal InterPhalangeal) joints as shown in Fig. 1 [14]. For an object grasping and manipulation, an initial finger configuration is properly determined and successive finger configurations should be assigned by combining those joints appropriately. If there exists a redundancy in a finger mechanism, the joint configuration for a fingertip position is not unique. In this case, a joint motion planning strategy is required for assigning a finger configuration effectively. The manipulability measure is useful for finding an optimal solution in the case [15]. Recently, this concept was applied to the MJP algorithm that assigns successive optimal finger configurations during an object manipulation [13]. It is incorporated as follows:

MJP algorithm

1) Specify a feasible fingertip position.
2) Determine the Jacobian of the finger.
3) Find all joint candidates satisfying the range of orientation with a proper deviation.
4) Compute the manipulability measure for all available joint combinations.
5) Choose the set of joint angles with the maximum value of manipulability in the feasible range of each joint.
6) Assign these angles as the corresponding joint angles.
7) Return to the step 1) and repeat the procedure for the given fingertip trajectory.

Note that the assigned finger configuration by using the MJP algorithm is optimal at each fingertip position in terms of the manipulability measure. However, the optimal procedure may cause undesirable trouble in the realtime finger manipulation because the configuration of the finger should be in the best posture at each time. So, it is an interesting point to analyze such a problem by experimental works.

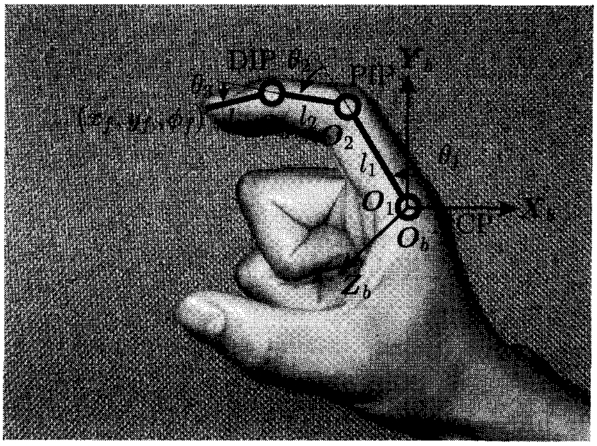


Fig. 1. A humanoid finger with three joints.

2.2. ICJP

In general object manipulations by multiple fingers, all of the fingertip movements should be combined adequately, and facilitative finger control is also desirable as much as possible. In this viewpoint, many researchers tried to utilize the feature in a human finger into robotic applications [9]. In fact, a biomimetic approach is required for implementing human-like finger motions. Recently, an interphalangeal coordination-based joint motion planning method (ICJP) was proposed and its merit was confirmed through a typical simulation study [13], It has been known that the ICJP method enables us to get an effective joint motion planning, and thus more facilitative finger motion is available. In the simulation, an intuitive coordination model observed in the movements of human fingers was applied to plan the configuration of a robotic finger. However, it is not enough to show the trend of resultant torque command certainly.

For more reliable humanoid fingers, an experimental verification is actually required, and thus the current paper tried to characterize a certain interphalangeal coordination in human fingers by

Fig. 2. A CyberGlove system for a human hand.

using a CyberGlove data acquisition system in Fig. 2. The trajectories of fingertips obtained by repeated grasping actions have been plotted in Fig. 3, where each trajectory has been computed by kinematic relations indirectly using the actual joint angles measured by joint sensors. As a result, it is obviously confirmed that the movement of DIP joint in each finger depends on the PIP joint, and there exists a linear relationship approximately:

$$\theta_3 = \lambda_o \theta_2. \tag{1}$$

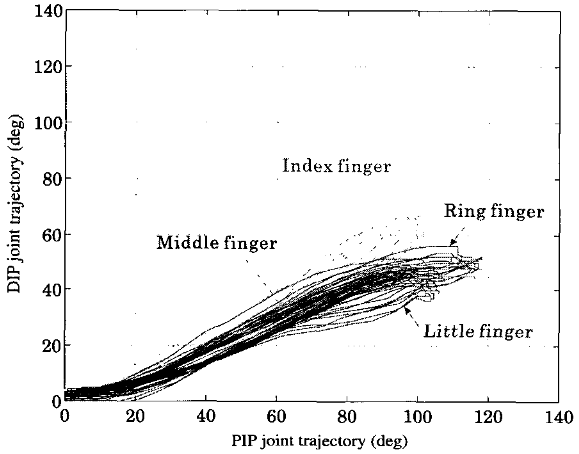


Fig. 3. Trajectories of the PIP and DIP joints.

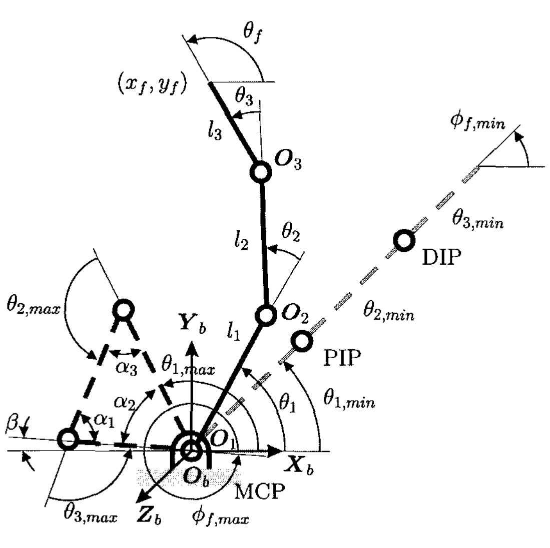


Fig. 4. Feasible postures of the index finger.

If one wants to utilize such a bio-mimetic property in a human finger for the applications to humanoid fingers, a strategy how to prescribe such a coordination factor for a given humanoid finger is necessary. In [13], a virtual triangle model in Fig. 4 was considered for the purpose. Based on the model, the maximum motion range of a finger can be characterized feasibly and an adequate interphalangeal coordination factor between DIP and PIP joints can be determined by

$$\lambda_o = \frac{\theta_{3,max}}{\theta_{2,max}}, \tag{2}$$

where $\theta_{2,max}$ and $\theta_{3,max}$ denote the maximum angles of the two joints. They are determined by

$$\theta_{2,max} = 180^o - \alpha_3, \tag{3}$$

$$\theta_{3,max} = 180^o - \alpha_1, \tag{4}$$

where

$$\alpha_3 = sin^{-1}\left\{\frac{l_3}{l_1} sin\alpha_1\right\}, \text{ and}$$

$$\alpha_1 = cos^{-1}\left\{\frac{(l_2)^2 + (l_3)^2 - (l_1)^2}{2l_2 l_3}\right\}.$$

In addition, the maximum angle of the MCP joint is determined by

$$\theta_{1,max} = 360^o - (\theta_{2,max} + \theta_{3,max}) - \beta, \tag{5}$$

where β denotes the angle from the line of distal phalanx to the horizontal axis of the base frame at the flexion posture, and it can be assigned properly according to the purpose of users in real applications. In this paper, β has been set as 0 degree such that the distal phalanx lies on the palm(or the horizontal axis of the base frame) at the maximum flexion posture. The maximum angle of each joint is also used to determine the initial finger configuration.

Accordingly, it is known from (2) that the interphalangeal coordination factor can be straightforwardly determined by using the kinematic parameters of a finger. This means that an interphalangeal factor can be effectively adopted even though the kinematic parameters are different from fingers. On the other hand, once an initial finger configuration for an object grasping and manipulation has been determined, it is necessary to confirm the original λ given by (2) whether it is compatible with the initial configuration. So, it is significant to check the additional interphalangeal coordination factor λ_s from the initial configuration as follows:

$$\lambda_s = \frac{\theta_{3s}}{\theta_{2s}}, \tag{6}$$

where θ_{3s} and θ_{2s} represent the initialized angles of the DIP and PIP joints of a finger as shown in Fig. 4, respectively. Thus, the reasonable interphalangeal coordination ratio λ is resultantly assigned by comparing those two factors:

$$\lambda = \begin{cases} \lambda_s & \lambda_s \le \lambda_o \\ \lambda_o & \lambda_s > \lambda_o. \end{cases} \tag{7}$$

Then, by applying (7) to the original Jacobian, we have

$$\dot{u}(t) = G_{\phi}^{u}\,\dot{\phi}(t), \tag{8}$$

where $\dot{u}(t) = [\,\dot{x}_f(t)\;\; \dot{y}_f(t)\;\; 0\,]^T$, $\dot{\phi}(t) = [\,\dot{\theta}_1(t)\;\; \dot{\theta}_2(t)\;\; \dot{\theta}_3(t)\,]^T$, and

$$G_{\phi}^{u} = \begin{bmatrix} -l_1 s_1 - l_2 s_{12} - l_3 s_{123} & -l_2 s_{12} - l_3 s_{123} & -l_3 s_{123} \\ l_1 c_1 + l_2 c_{12} + l_3 c_{123} & l_2 c_{12} + l_3 c_{123} & l_3 c_{123} \\ 0 & -\lambda & 1 \end{bmatrix}.$$

Also, the velocity vector at the joint space can be obtained by

$$\dot{\phi}(t) = G_{u}^{\phi}\,\dot{u}(t), \tag{9}$$

where G_u^{ϕ} denotes the inverse of G_u^{ϕ}. As a result, the joint angles of the finger can be updated by

$$\phi(t+dt) = \phi(t) + \dot{\phi}(t)dt, \tag{10}$$

where dt is the sampling time of the finger control system.

Through the analysis, the overall procedure of the ICJP algorithm is summarized by

ICJP algorithm

1) Specify an initial fingertip position, x_f and y_f.
2) Determine an initial joint configuration by MJP.
3) Determine λ by (7)
4) Determine the Jacobian G_{ϕ}^{u} in (8).
5) Find the next joint angles through (8)~(10).
6) Return to the step 4) and repeat the procedure until the terminal trajectory.

It is important to note that a human finger for general manipulations usually uses two motions such as flexion/extension and adduction/abduction. Basically, the ICJP algorithm utilizes to plan the joint trajectories for a given flexion/extension fingertip motion. Nevertheless, it can be applied to general manipulations with ease by adopting an additional joint, i.e., MCP that is available for adduction/ abduction motion. It is because the motion planning of flexion/extension in human fingers is not affected by that of adduction/abduction. Also, a major advantage of using ICJP is to use an appropriate interphalangeal factor for each finger which is dependent on its kinematic parameters. So, it is compatible for fingers with different dimension. But Secco *et al.* [16] confined the interphalangeal factor as a fixed value, and thus the task compatibility as fingers may be limited.

3. EXPERIMENTAL VERIFICATION

This section presents two experimental works for circular and complex rose motions of a robotic finger and verifies the practical effectiveness of the proposed ICJP method compared with the MJP method.

3.1. Approach for experimental works

A four-fingered robot hand and a PC-based hand control system as shown in Fig. 5 have been used for experimental works. All fingers have the same structure, and each finger has four revolute joints which are driven by an AC servomotor(Model No. YR-KA01-A000 or YR-KA02-A000, Yasukawa Electric Co.) with an encoder. A Pentium-IV(2.2GHz) computer with Linux is used for the experiment. The control algorithms are coded in C language and the control signal made by a PID controller is executed every 5 ms with the aid of the real-time operating system, RTX [17]. The PID gains for each joint are chosen by 2.4, 0.00375, and 0.075, respectively. For safety, the torque output for driving joints is limited by ± 1.7 Nm in software.

For convenient experimental verification, one finger in the hand has been tested by using the joint trajectories planned by the two different methods, ICJP and MJP, with the same conditions in the previous simulation study [13].

3.2. Experimental work for circular motion

The purpose of this experiment is to validate a circular motion of the robotic finger planned by using the ICJP and MJP methods. A circular trajectory is actually the fundamental function of a fingertip for an object manipulation. In this experiment, it is given by

$$x_f(t) = x_0 + r_0 sin\left(\frac{2\pi}{t_f}t\right)$$

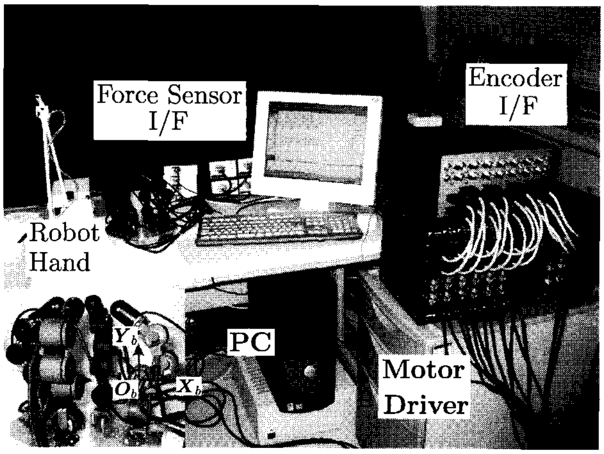


Fig. 5. A four-fingered robot hand and its control system.

and

$$y_f(t) = y_0 + r_0\left\{1 - cos\left(\frac{2\pi}{t_f}t\right)\right\},$$

where the initial fingertip positions, x_0 and y_0, are selected by -0.0225 and 0.0900, respectively. Each parameter of the radius r_0 and the terminal time t_f is set as 0.01m and 1.6s. Also, the joint angles for the given initial fingertip position have been initialized by MJP as follows: $\theta_1 \cong 48.96^o$, $\theta_2 \cong 91.15^o$, and $\theta_3 \cong 32.89^o$. The resultant joint coordination ratio λ between DIP and PIP joints is assigned as 0.3126.

In general, a stabilized finger motion results in a precise object manipulation. In order to confirm a stabilized finger motion, it is useful for demonstrating the trend of the resultant fingertip trajectory controlled. So, this paper identifies the results of trajectory following and error shown in Figs. 6 and 7, respectively. From these figures, it is confirmed that the fingertip's trajectory following by employing the

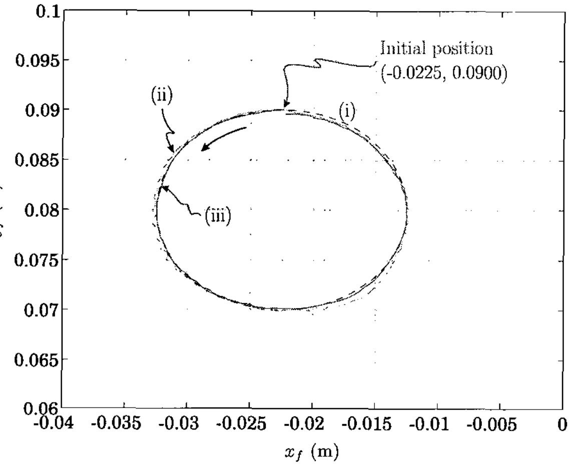


Fig. 6. Trajectory following result of the finger: (i) desired trajectory, (ii) actual trajectory when the MJP method is employed, and (iii) actual trajectory when the proposed ICJP method is employed.

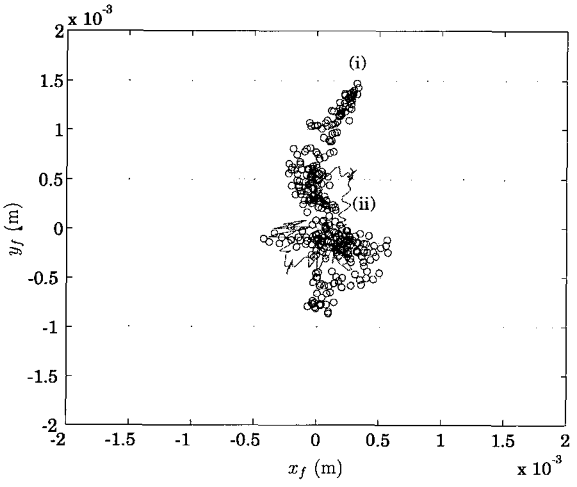
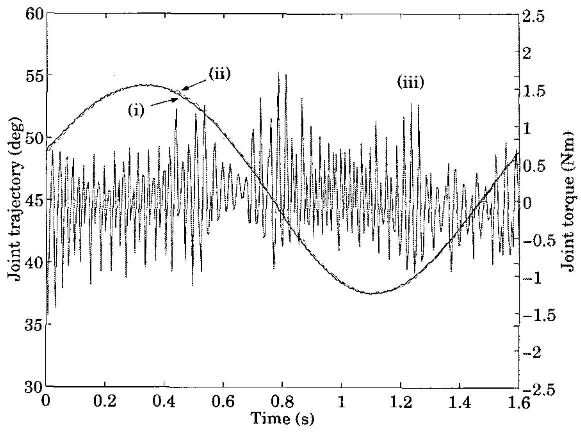
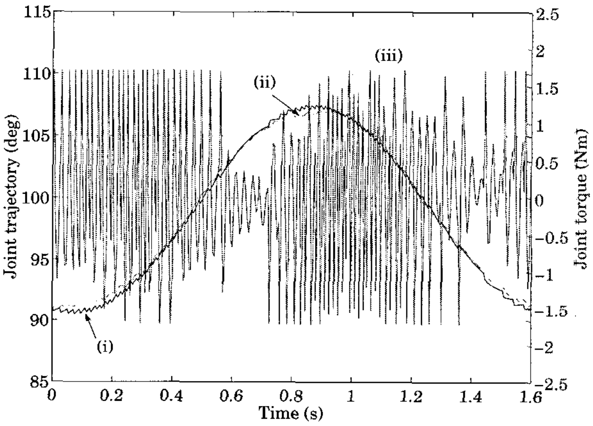


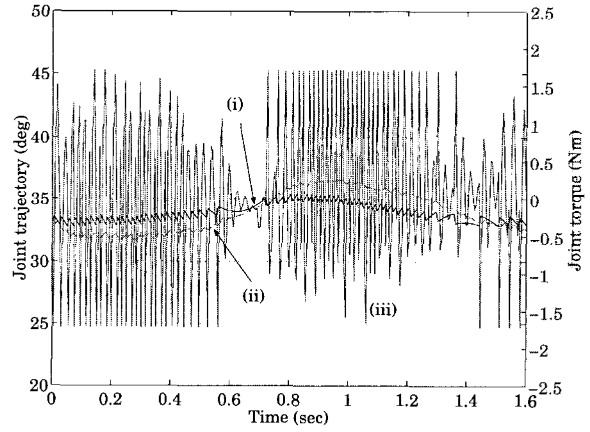
Fig. 7. Tracking error at the circular motion: (i) MJP and (ii) ICJP.



(a) MCP joint, θ_1.



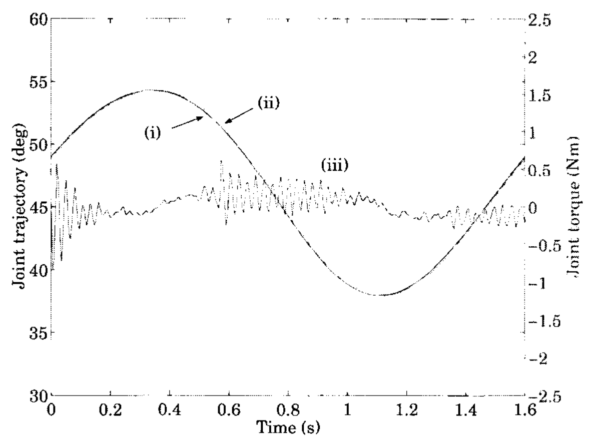
(b) PIP joint, θ_2.



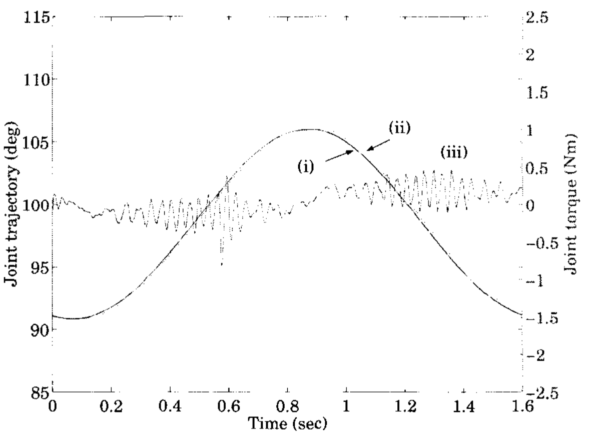
(c) DIP joint, θ_3.

Fig. 8. Joint trajectories and torque signal for the circular motion when the MJP method is employed: (i) planned trajectory, (ii) actual trajectory, (iii) actual joint torque.

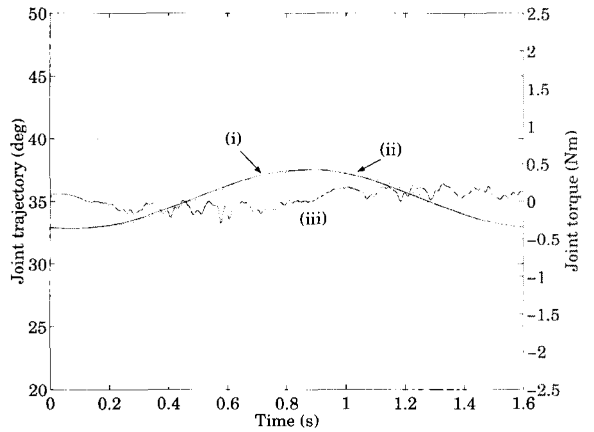
MJP method is rough, while the response by the ICJP method is very smooth. The tracking error range is also more small in the case of using the ICJP method. Here, in the practical implementation aspect, it is valuable to analyze the reason why the fingertip's trajectory can be more stabilized by ICJP. In order to illustrate such a trend, it is necessary to check up each joint control performance.



(a) MCP joint, θ_1.



(b) PIP joint, θ_2.



(c) DIP joint, θ_3.

Fig. 9. Joint trajectories and torque signal for the circular motion when the proposed ICJP method is employed: (i) planned trajectory, (ii) actual trajectory, (iii) actual joint torque.

Thus, this paper tried to confirm the original joint trajectory planning, the actual joint motion, and the actual joint torque profiles of all joints during the finger manipulation in Fig. 6. Those experimental results are shown in Figs. 8 and 9, respectively. The planned trajectory, the actual trajectory, and the torque signal for driving each joint are presented in one plot for convenience. From those figures, it is observed that the joint trajectories in the case of using MJP have been planned irregularly, while those by ICJP have been planned as a natural pattern relatively. More specifically, the trajectories of the PIP and DIP joints have been planned with remarkable alternations when the MJP method is employed, but such phenomenon is not occurred by ICJP. This observation leads us to think about the reason why such an uneven trajectory may be planned by MJP. Nevertheless, the finger configuration planned by MJP is optimal in terms of manipulability criterion. That is, the MJP method plans each finger configuration to be in the best posture with regard to the manipulability criterion at each time. This effort may be strict and causes each joint trajectory to be irregular as shown in Fig. 8(i). From this sense, it is pointed out that although the finger intends to have a skillful posture by using MJP, much trouble can be loaded to real joint actuation because each joint should try to adapt to the hard motion planned. Practically, such irregularly shaking joint motions make the controller produce greatly exciting torque signals as shown in Fig. 8(iii). As a result, it is remarked that some trembling effect can be modulated in the actual fingertip motion as shown in Fig. 6(ii). In this case, if the controller's gains are increased to reduce the tracking error, the torque change may become serious. Since such excessively fluctuating torques cause undesirable jerk motion at the fingertip space, it should be alleviated in precise object manipulations.

On the other hand, those responses by ICJP shown in Fig. 9 are very moderate relatively. This is basically because the desired joint trajectory for the task has been planned in a very natural pattern as shown in Fig. 9(i). Such smooth and continuous joint trajectories result in a well-balanced torque pattern as shown in Fig. 9(iii). It is also analyzed that those tender torque commands contributed to make the resultant stable fingertip motion shown in Fig. 6. This implies that stably planning of joint motions plays an important role for stable finger control. As a result, it is remarked that the interphalangeal coordination-based joint motion planning method is practically useful for stable finger operations.

3.3. Experimental work for rose motion

The second experiment treats a rose motion for implementing a more complex fingertip's manipulation. At the same initial finger configuration, the fingertip trajectory is give by

$$x_f(t) = x_0 + r_x cos\left(\frac{4\pi}{t_f}t\right)cos\left(\frac{2\pi}{t_f}t\right) \text{ and}$$

$$y_f(t) = y_0 + r_y cos\left(\frac{4\pi}{t_f}t\right)sin\left(\frac{2\pi}{t_f}t\right),$$

where the parameters of r_x and r_y are set as 0.0035m. Since the given trajectory consists of a quadrantal curve, it is useful for modulating a complex finger motion.

Figs. 10 and 11 show the results of trajectory following and error for the rose motion, respectively. The planned and actual joint trajectories, and the actual joint torques for the given fingertip motion are plotted in Figs. 12 and 13, respectively. From these figures, it is certainly confirmed that the actual fingertip trajectory by utilizing ICJP is more stable

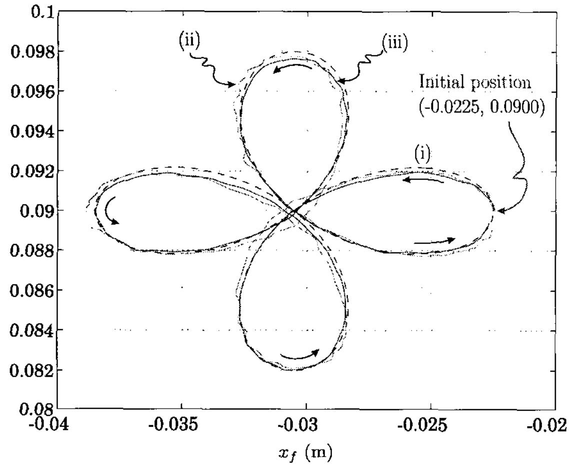


Fig. 10. Trajectory following result of the finger: (i) desired trajectory, (ii) actual trajectory when the MJP method is employed, and (iii) actual trajectory when the proposed ICJP method is employed.

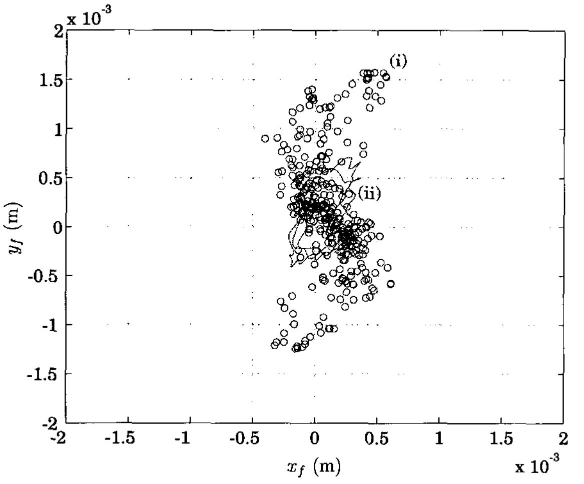
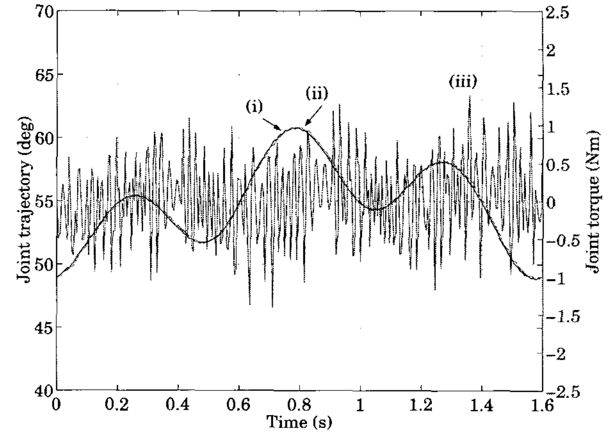
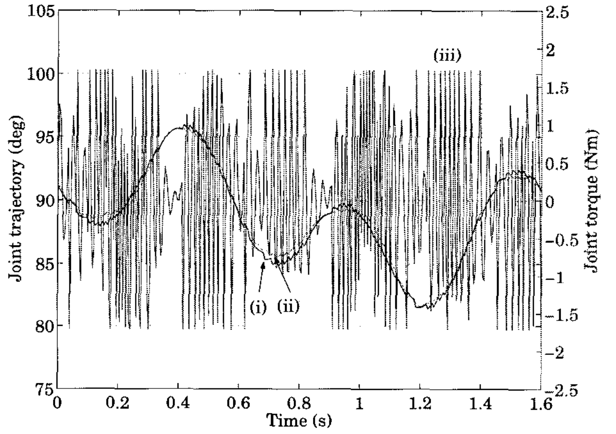


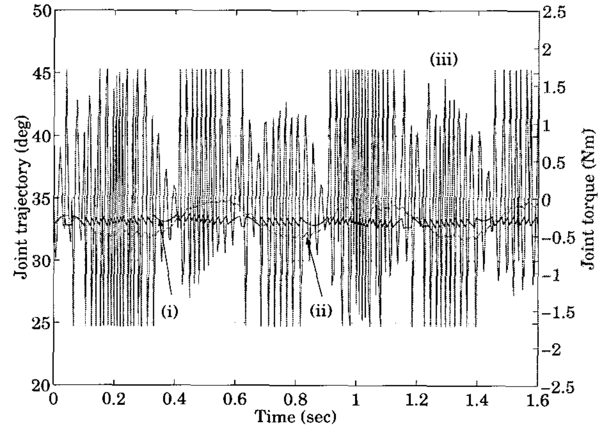
Fig. 11. Tracking error at the rose motion: (i) MJP and (ii) ICJP.



(a) MCP joint, θ_1.



(b) PIP joint, θ_2.

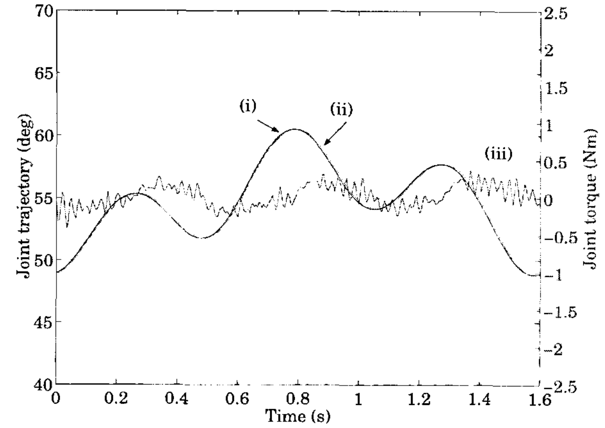


(c) DIP joint, θ_3.

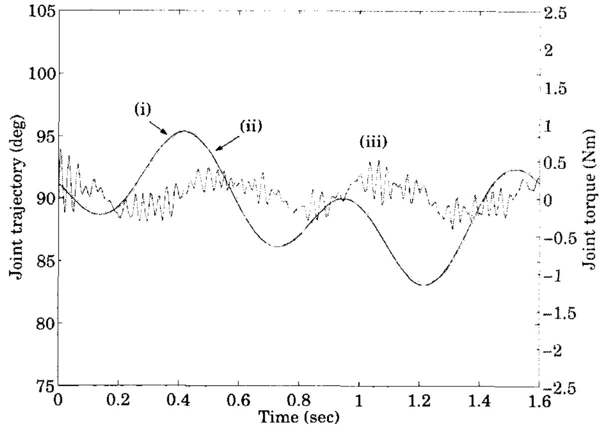
Fig. 12. Joint trajectories and torque signal for the rose motion when the MJP method is employed: (i) planned trajectory, (ii) actual trajectory, (iii) actual joint torque.

than that by MJP. This is because the ICJP approach provides a successive trajectory planning and leads the more moderate torque pattern that controls each joint stably.

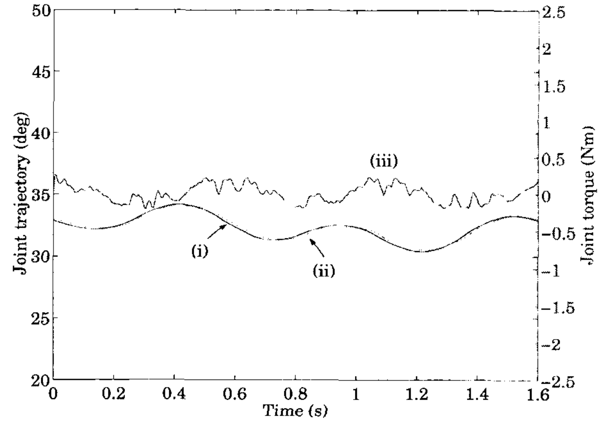
As a result, the effectiveness of ICJP and superiority of ICJP over MJP have been proved through experimentation. It is pointed out that the accuracy of a fingertip motion for an object manipulation remarkably depends on the joint motion planning strategy. Actually, the more a joint trajectory of a finger is planned naturally, the more the finger can be controlled facilitatively. If the ICJP method is employed in the process of joint motion planning, it is possible to initialize an effective configuration of a finger and also to plan a natural joint trajectory in an on-line manipulation process, and the resultant control performance of the finger can be improved certainly. Therefore, it is expected that the ICJP method can be applied to precise control of humanoid fingers [3,5] as well as prosthetic fingers [11,18].



(a) MCP joint, θ_1.



(b) PIP joint, θ_2.



(c) DIP joint, θ_3.

Fig. 13. Joint trajectories and torque signal for the rose motion when the proposed ICJP method is employed: (i) planned trajectory, (ii) actual trajectory, (iii) actual joint torque.

4. CONCLUDING REMARKS

In this paper, several experiments for an interphalangeal coordination-based joint motion planning method (ICJP) have been implemented. Through the experimental works, the effectiveness of ICJP and superiority of ICJP over MJP have been shown. The experimental verification gives a reason to recognize that stable joint motion planning plays an important role in achieving precise and facilitative finger control. Practically, such an effective joint trajectory planning results in a well-balanced torque command that is essentially required for real finger manipulations. Thus, it is concluded that the proposed interphalangeal coordination-based joint motion planning method makes a great contribution in manipulating tasks by dexterous humanoid fingers as well as prosthetic fingers.

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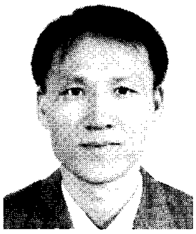

Byoung-Ho Kim received the B.S. and M.S. degrees in the Dept. of Electronics Engineering from the Kumoh National Institute of Technology in 1985 and 1994, respectively. In 2001, he received the Ph.D. degree in the Dept. of Electronics Engineering from Hanyang University. From 1989 to 1993, he was a Researcher with the Dept. of Research and Development of LG Innotek, Kumi, Korea. From 1995 to 1999, he joined the Humanoid Development Project with the Intelligent Robotics Research Center of the Korea Institute of Science and Technology (KIST), Seoul, Korea. From 2002 to 2004, he was a JSPS (Japan Society for the Promotion of Science) Post-doc Fellow with the Dept. of Robotics, Ritsumeikan University, Japan. From 2004 to 2005, he was a Frontier Research Scientist with the Bio-Mimetic Control Research Center in the Institute of Physical and Chemical Research (RIKEN), Nagoya, Japan. Dr. Kim is currently with the Division of Electrical and Mechatronics Engineering, Kyungsung University, Busan, Korea as an Assistant Professor. His research interests include bio-mimetic robotic systems, multi-fingered hands, soft manipulation, mobile manipulation, intelligent control for humanoids, and medical science. He is a Member of IEEE, IEEK, Institute of Control, Robotics, and Systems, Korean Institute of Intelligent Systems, and Korean Society of Precision Engineering.