博士論文

Biomechanics of fingers in baseball throwing

（野球の投球動作における手指のバイオメカニクス研究）

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Acknowledgement

Abbreviations

AD: Analog-digital

CNS: Central nervous system

COM: Center of mass of whole body

COP: Center of pressure of force acting on the ball due to the index finger and middle finger

DIP: Distal interphalangeal

EL: Lateral Epicondyle

EM: Medial epicondyle

Ext: Extension

Flex: Flexion

FT: Fingertip

MP: Metacarpophalangeal

MPI: Magnetic resonance imaging

MPM: MP joint of middle finger

PD: Proximal to distal

PIP: Proximal interphalangeal

Pro: Forearm pronation

REL: Ball release

RELT: REL from the thumb

ROM: Range of motion

RW: Radial wrist

SD: Standard deviation

Sup: Forearm supination

UW: Ulnar wrist

WJC: wrist joint center

CHAPTER 1

INTRODUCTION

1-1. Preface

Throwing motion is unique motion for human. In ordinary life and sports activities, there are several types of throwing motion. Such as underarm throwing when you pass some object to the other for a short distance, darts throwing that requires accuracy, and javelin throwing that aims distance, etc. Specifically, dynamic overarm throw is the most typical throwing style and motion that only human can perform.

Of sports activities, baseball throwing requires both ball velocity and accuracy. Additionally, it is very complex multi-joint movement. Joint rotations occur sequentially from proximal joints to distal joints. Also, the pitcher must throw a baseball to the strike zone that is 18.44 m far away from pitcher quickly and accurately. Accomplishing these tasks requires complex control and coordination of many body segments. To understand these skills, specifically, information about the shoulder, elbow, forearm, wrist and fingers of the throwing arm is essential. The kinematics (e.g., joint rotation) and kinetics (e.g., joint torque, work) of the shoulder, elbow, forearm, and wrist are well examined. Recently, force acting on the finger during baseball pitching have been measured. However, detailed kinetic analysis of fingers (e.g. torque, power, and work) has not been reported. It was indicated that a few milliseconds' delay from fingers' release timing leads to the change of ball trajectory significantly. Additionally, in baseball pitching, the pitchers throw not only a fastball that is the most fundamental pitch but also various breaking ball like ‘curve’, ‘slider’ and ‘change-up’ to get the batter out. The coaches often emphasize that it is important that the pitcher throws a fastball and breaking ball as the same throwing motion as possible not to be judged a pitch before ball release by the batter. That is, it is ideal that the motion of all segments except fingers is the same among pitches. Probably, in a skilled pitcher, the movement in large segment (e.g. trunk, shoulder, elbow) is similar among pitches, and fingers will control ball trajectory and spin characteristic. To grip the ball and release it during baseball pitching, a pitcher must supply an adequate fingers torque. Thus, it is considered that control of fingers torque is a significant factor for baseball pitching. The information about finger torque during baseball throwing will assist a pitcher and coaches in development of the skill and the prevention for injury. However, the mechanisms how fingers torque is controlled during ball throwing to accomplish these tasks remain to be elucidated.

The mechanisms how fingers torque is controlled during baseball throwing were investigated in this thesis from the aspects of biomechanics. Analyzing the human movement quantitatively from the biomechanical aspects is an effective way to understand how human bodies are controlled. For executing baseball throwing successfully, ball velocity should be generated, and at the same time, ball release has to be controlled accurately. Additionally, pitchers are required to throw several pitch types with the same body movement. Therefore, the biomechanical analyses in this thesis were conducted from two aspects, 1) how fingers torque during ball throwing is controlled to accomplish both generation of ball velocity and accurate ball release, and 2) how fingers torque during baseball throwing is controlled to throw several pitch types. That is, the role of fingers torque during baseball throwing was elucidated biomechanically in terms of these two aspects.

1-2. Control of Grip and Release

In baseball throwing, generating large ball velocity and achieving accurate ball release are necessary. Some researchers reported that the proximal-to-distal segmental sequence is essential for accelerating the distal segment (Pappas et al., 1985; Feltner, 1989). Thus, it is required that the whole arm moves like a whip to accelerate the ball. Specifically, the fingers of the throwing hand are final segment that transfers kinetic energy produced by whole body to the ball.

In addition, delicate control of fingers is necessary for achieving accurate ball release. Throwing a baseball requires grip and release motion. It is reported that there are two fundamental grip ways, first identified by J. R. Napier, and named by him the ‘precision grip’ and ‘power grip’ (Napier, 1965). ‘Precision grip’ represents that grasping a sphere (softball, baseball, and cricket ball) in a manner that allows precise control of release. ‘Power grip’ represents that grasping a cylinder (tennis racquet, golf club and cricket bat) with strength sufficient to withstand a violent impact. In precision grip, transiting from grip to release instantly is necessary. If this transition is fail, the ball will deviate widely from the course throwers aim. Thus, pitchers must control grip force adequately. Skilled throwers can grip the ball with a force proportional to ball weight and intended ball speed (acceleration) (Hore et al., 2001). Also, skilled throwers achieve ball accuracy by computing finger force/stiffness based on state estimation of hand acceleration (Hore et al., 2011). Throwers cannot accomplish a given task only by the feedback control during high speed motion. It has been suggested that internal models are used to predict the resultant state of the task when the assumed motor command are executed, and they are used to control the movements in the feedforward manner (Flanagan & Wing, 1997; Kawato, 1999). These results indicate that skilled throwers achieve transition from grip to release instantly by an anticipatory control (feedforward computation).

Precise neuromuscular control of fingers muscles permits submillisecond release times needed for throwing accuracy. Some previous studies have investigated fingers kinematics and accuracy (Hore et al. 1996a,b). The timing of fingers extension is more important for an accurate overarm throw than the timing of the onset of rotation at a more proximal joint. In fact, a 1-ms delay in fingers extension causes a change in direction of 2.2° (Hore et al. 1996b). In summary, it is considered that the timing of fingers movement is a significant factor for achieving accurate ball release.

From these studies, it is anticipated that fingers movement has a critical role in both generation of ball velocity and accurate ball release. However, the mechanism how fingers are controlled to accomplish both generation of ball velocity and accurate ball release is not understood well.

To understand the mechanical mechanism of groups of upper limb muscles during ball throwing, the inverse dynamics method for calculating the net joint torque, power, and work has been used (e.g., Hirashima et al., 2007; Nissen et al., 2007). However, finger movements have not been considered in the conventional model yet, and kinetic analyses of fingers have not been reported. Therefore, the functioning of fingers torque during ball throwing is not yet understood. Understanding the functioning of fingers for accomplishing both generation of ball velocity and accurate ball release would contribute to performance enhancements of athletes and to ensure the proper training methodology.

1-3. Fastball and Curveball

Ball velocity and accuracy are important skill elements for most baseball pitchers. However, these skills are only one aspect of pitching performance. For confusing the batter, skilled pitchers throw many different types of pitches. Specifically, the fastball is said to be the most important pitch in any pitcher's arsenal, and a curveball is recommended as best used to supplement the pitcher's ability to throw a fastball (Jordan, 1988). Some researchers investigated ball velocities and rotations during fastball and curveball pitches (e.g., Selin, 1959; Jinji and Sakurai, 2006). In these studies, the average ball velocity for the fastball was significantly greater than the average velocity of the curveball. Though the average rotational velocities of these two pitches were rather comparable, the directions of the spin were almost opposite. The fastball was characterized by backspin whereas the curveball had a combination of topspin and sidespin. The differences in the velocity and rotation between the two pitches will cause the different flight patterns, and allow to deviate the timing and swing trajectory of the batter (Sakurai et al., 1993). It is expected that there are some different movement characteristics to produce the differences in velocity and ball rotation between the two pitches.

In a previous study, the action of the thumb, index, and middle fingers in releasing the fastball and the curveball was examined (Stevenson, 1985). The fastball left the thumb first followed by either the middle or index fingers. On the other hand, approximately 75 % of the curveball pitches were thrown in a thumb-middle-index sequence and approximately 25 % of the curveballs had a middle-thumb-index release sequence. These results suggest that delicate control of fingers play the crucial role for generating characteristic spin during fastball and curveball pitches. However, this study dealt with only kinematics aspects of the fingers movements, and the detailed mechanism how fingers during baseball throwing are controlled to throw several pitch types is not understood well. For a more definitive interpretation of the different mechanism of the two pitches, it is necessary to examine the changes of fingers joint torque and work. In this thesis, control of fingers during fastball and curveball pitches was investigated by conducting kinetic analysis.

1-4. Purpose of the Thesis

The purpose of this thesis as a whole was to investigate how fingers torque are controlled to perform baseball throwing. Firstly, biomechanical approaches were used to examine the mechanism of fingers torque control to execute baseball throwing. The mechanism of fingers torque control during baseball throwing was investigated in terms of two aspects. One was how fingers torque during ball throwing is controlled to accomplish both generation of ball velocity and accurate ball release, and the other was how fingers torque during baseball throwing are controlled to throw several pitch types. In chapter 2, we developed a link segment model considering fingers to clarify the roles of fingers torque in ball throwing, and its validity was evaluated. In chapter 3 and 4, to focus on fingers' general function during ball throwing, the mechanism of fingers' torque control to accomplish both generation of ball velocity and accurate ball release was examined by analyzing ball throwing motion under various ball velocity. In chapter

5, to extend our findings to actual baseball pitching where ball velocities are much higher, the mechanism of fingers' torque control to throw several pitch types was investigated by analyzing fastball and curveball throwing motion under the condition that is close to the actual pitching.

1.5 Organization of the Thesis

1.5.1 Chapter 2: Development of Fingers Model During Ball Throwing

Baseball throwing requires both ball velocity and accuracy, and it is very complex multi-joint movement. Accomplishing these tasks requires complex control and coordination of many body segments. While the kinematics and kinetics of the shoulder, elbow, forearm, and wrist are well examined, kinetic analyses of fingers motion have not been reported. It was indicated that a few milliseconds' delay of fingers' release timing leads to the change of ball trajectory significantly. In baseball pitching, it is ideal that the motion of all segments except fingers is unified among pitches. From these results, it is considered that control of fingers torque is a significant factor for baseball pitching.

Some researchers have investigated kinetics of hand during pitching (e.g. Solomito et al., 2014; Nissen et al., 2007). For technical reason, these previous studies have used a linked segment model that regarded a palm, fingers and a ball as one 'hand' segment. Thus, finger movements have not been considered in the conventional model yet, and the functioning of fingers torque during ball throwing is not yet understood. Therefore, in Chapter 2, we developed a link segment model considering fingers (fingers model) to clarify the roles of fingers in ball throwing, and its validity was evaluated. To focus on fingers' general function during ball throwing, this study was not conducted with a specific throwing style, but with aimed throwing from a static standing position. Also, this study's second objective was to reveal the wrist joint torque's difference between the conventional model and the finger model in which the finger segment was considered rigid.

1.5.2 Chapter 3: Timing Control between Wrist Torque and Finger Torque during Ball Throwing

In Chapter 2, we developed a link segment model considering fingers (fingers model) to clarify the roles of fingers in ball throwing.

In ball throwing, the proximal-to-distal segmental sequence (P–D sequence) was identified by Pappas et al. (1985) and Feltner (1989), who considered the segmental sequence essential for effective generation of great speed in the distal segment. However, whether P–D sequence from wrist to finger occurs was not examined. Thus, this study's objective was to examine the central nervous system's (CNS's) timing control between wrist torque and finger torque. A commonly used inverse dynamics method to compute the net joint moments was used. This technique allows us to know the force and moment at each joint non-invasively. Therefore, computing net joint moments by the inverse dynamic method help us understand how timing between wrist torque and finger torque are controlled to accomplish both generation of ball velocity and accurate ball release.

1.5.3 Chapter 4: Control of Fingers Torque during Ball Throwing under Different Ball Velocity

In Chapter 3, timing control between wrist torque and finger torque during aimed throwing was investigated. In addition to that, in Chapter 4, control of fingers torque during ball throwing under different ball velocities (slow, medium, fast) was examined. In baseball, pitchers throw a ball with wide range of ball velocity keeping accuracy. However, ball velocities analyzed in Chapter 3 were slow (7.8 ± 0.7 m/s) , and its velocity range was also restricted. It has previously been shown (Hore et al., 2001) that fast throws generate larger grip force than slow throws. Therefore, it was examined if fingers torque and work also increased with increasing ball velocity. Additional aspects of how fingers torque during ball throwing are controlled to accomplish both generation of ball velocity and accurate ball release were examined in Chapter 4.

1.5.4 Chapter 5: Biomechanical Role of Fingers during Fastball and Curveball Pitches

In Chapter 3 and Chapter 4, to focus on general function of fingers during ball throwing, the first question of the study how fingers torque during ball throwing is controlled to accomplish both generation of ball velocity and accurate ball release was discussed. In Chapter 5, to extend our findings to actual baseball pitching where ball velocities are much higher, how fingers torque during baseball throwing is controlled to throw several pitch types was discussed. In baseball, pitchers throw not only the fastball but also many different types of breaking ball to get batter out. Specifically, curveball is one of the representative breaking balls. However, kinetic analyses of fingers during fastball pitches have not been conducted, and the mechanism how fingers during baseball throwing are controlled to throw several pitch types is not understood well. Thus, the mechanism how fingers torque is controlled to throw fastball and curveball was examined.

1.5.5 Chapter 6: *General Discussion*

The findings of the three studies were summarized and discussed to answer the two research questions, (1) how fingers torque during ball throwing is controlled to accomplish both generation of ball velocity and accurate ball release and (2) how fingers torque during baseball throwing is controlled to throw several pitch types. As a whole, it was discussed how fingers torque is controlled during baseball throwing.

CHAPTER 2

DEVELOPMENT OF FINGERS MODEL DURING BALL THROWING

2-1. Introduction

The role of hand and wrist joint during ball throwing has been investigated by previous studies (Hirashima et al., 2002, 2003; Debicki et al., 2004). These previous studies have used a linked segment model that regarded a palm, fingers and a ball as one 'hand' segment (Fig. 2-1) because spatial resolution of high speed camera was low and inertial properties at finger was not measured. However, a palm, fingers, and a ball each moves differently during ball throwing. The fingers are open first, and the ball rolls along the fingers (Hore et at, 1996). Some previous studies investigated kinematics of fingers (e.g. Stevenson, 1985; Watts et al., 2004). However, fingers movements have not been considered in the conventional model yet. In other words, finger torque's functioning during ball throwing is not yet understood. Therefore, this study's first objective was to develop a link segment model considering fingers to clarify the roles of fingers torque in ball throwing.

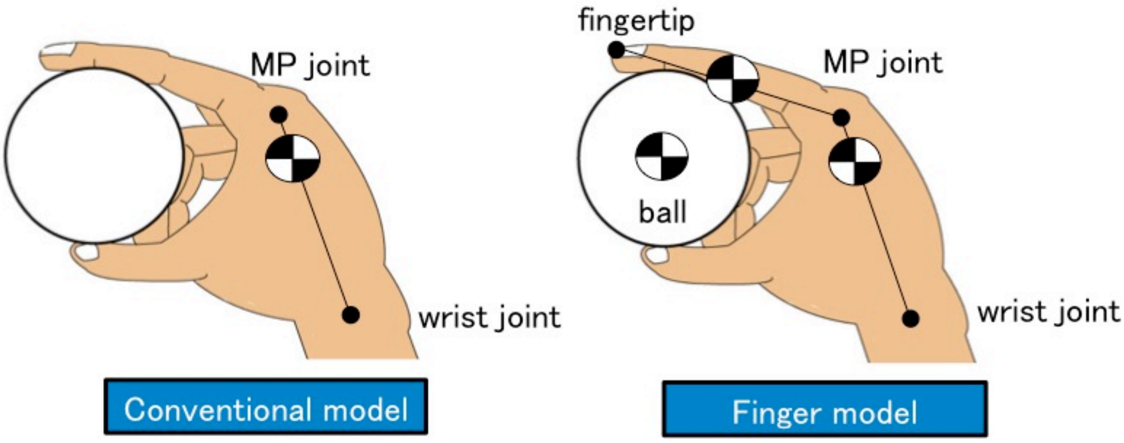


Fig. 2-1. Two types of hand model: "Conventional model" and "Finger model"

Conventional model makes the hand only one segment including a ball. Finger model divides the hand into a palm and finger segments, and a ball. The finger segment consists of the index, middle and ring finger.

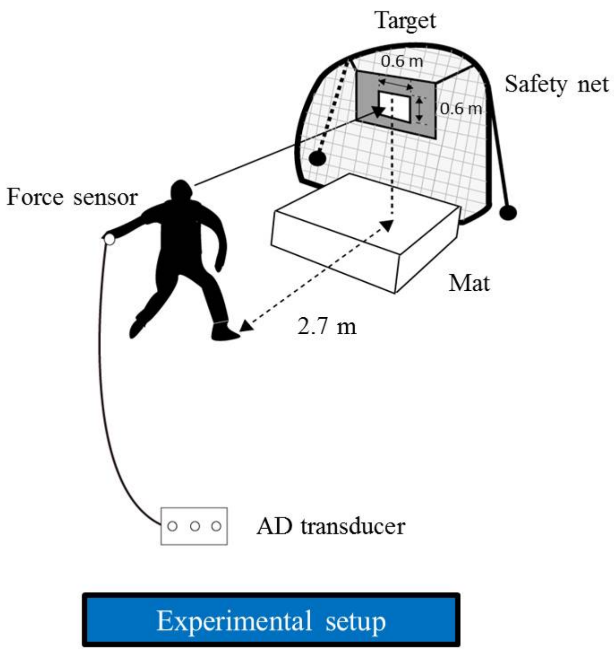
To focus on fingers' general function during ball throwing, this study was not conducted with a specific throwing style, but with aimed throwing from a static standing position. Also, this study's second objective was to reveal the wrist joint torque's difference between the conventional model and the finger model in which the finger segment was considered rigid. In conventional model, ball acceleration was identified with acceleration in COM of the hand segment (eqs.(2-4)). We expected that wrist flexion/extension torque in the conventional model is underestimated.

2-2. Methods

2.2.1 Experimental Design

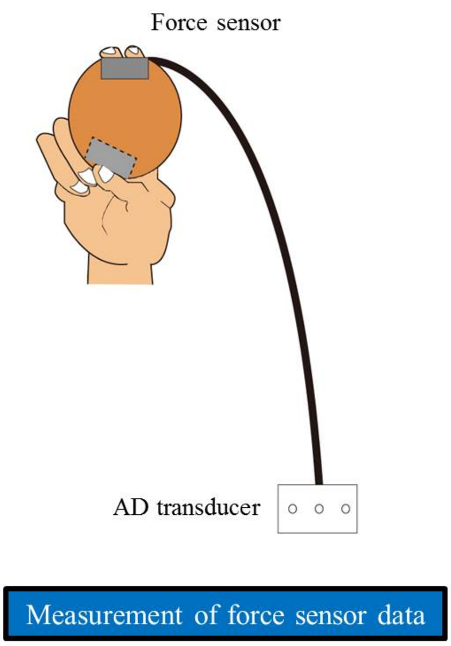
Seven healthy male subjects (age: 26 ± 4 years, mass: 69 ± 13 kg, height: 1.80 ± 0.07 m) participated in the experiment after providing informed consent. They were right-handed baseball players (mean baseball experience: 5 ± 4 years; range: 3～16 year). This experimental procedure was approved by the Ethical Committee of the Graduate School of Arts and Sciences of the University of Tokyo (reception number:342-2). During aimed throwing, all subjects were instructed to stand with their left foot forward and right toe contacting the ground. The subjects were instructed to throw the ball overhand toward a target accurately at slow-medium velocity (Fig. 2-2A). To absorb the traveling ball's shock, the target was made of cloth, and its size was 0.6 m × 0.6 m. The horizontal distance between the target and the left foot was 2.7 m, and the target's center height was eye-level. The target's surroundings were covered with a safety net and mat. Subjects gripped the ball with the first two fingers and the thumb, and additionally, by leaving a gap between the ball and the hand.

A



Target
0.6 m
0.6 m
Safety net
Force sensor
Mat
2.7 m
AD transducer
Experimental setup

B



Force sensor
AD transducer
Measurement of force sensor data

Fig. 2-2. A: Experimental setup and B: method of computing the force acting on ball at different finger position

Force sensor was buried in wooden ball to measure the force acting on ball from different fingers position. The extension cable was used to reduce the limitation of the movement by wired-force sensor.

2.2.2 Recording Movement

Seven reflective markers were attached to the subject, and two markers were attached to the wooden ball (Fig. 2-3). Markers on the fingers were 14 mm in diameter, and others (palm, forearm, and ball) were 19 mm in diameter. Motions were recorded using a 3D motion capture system (HAWK Digital System, Motion Analysis Corp., Santa Rosa, CA, USA). The sampling rate was set at 200 Hz, based on previous studies (e.g., Elliott et al., 1986; Sakurai et al., 1993). Instants of ball release (REL) from the thumb (RELT) and fingertips of the first two fingers were obtained by a high-speed camera at 1000 fps (MEMRECAM HX-6, nac Image Technology Inc., Tokyo, Japan).

2.2.3 Conventional Model and Finger Model

The "finger model" divides the hand segment into palm, three fingers, and ball segments (Fig. 2-1). The ball is assumed to be a mass-point and is attached to the finger segment until release. The index, middle, and ring fingers were assumed to form one rigid body, defined as extending from the middle finger's metacarpophalangeal (MP) joint to the fingertip. To calculate error in finger length, the maximal variation of finger segment length (l) when throwing a ball was calculated using positional data of markers attached to the middle finger. The calculated maximal variation was compared with finger length, which was measured with a tape measure before the experiment. The palm segment was defined as one rigid body from the wrist joint's center to the middle finger's MP joint—the same as the hand segment in the conventional model (Table. 2-1). The mass of the finger segment (m_F) was estimated as follows:

$$m_F = 6.1\times10^{-3}\times m_B\times0.5\times0.6, \qquad (2\text{-}1)$$

where m_B is the body mass, 6.1×10^{-3} is the hand to body mass ratio (de Leva et al., 1996), 0.5 implies that hand length divides equally into a palm and fingers, and 0.6 indicates that the finger segment comprises three of five fingers. In the conventional model, the ball's mass (m_{ball}) is added to the hand segment (Hirashima et al., 2003a). In the finger model, the palm segment's mass does not include the ball. The finger segment's center of mass (COM) was defined as the midpoint between the middle finger's MP joint and its tip. The finger segment was assumed to be of uniform density. The moment of inertia (*I*) was calculated as follows (Goto et al., 1971):

$$I = \frac{l^2}{12}m_F \qquad (2\text{-}2)$$

In the palm segment, the COM, and moment of inertia are the same as for the hand segment in the conventional model. The center of pressure (COP) of force acting on the ball by the fingers was located at the palmar aspect of the middle finger's tip.

					Radii of gyration		
	Endpoints		Mass (kg)	COM (%)	x axis (%)	y axis (%)	z axis (%)
Segment	**Origin**	**Other**					
Conventional model							
Hand	**WJC**	**MPM**	$(6.1 \times 10^{-3} \times m_B) + m_{ball}$	79.0	51.3	40.1	62.8
Finger model							
Palm	**WJC**	**MPM**	$6.1 \times 10^{-3} \times m_B$	79.0	51.3	40.1	62.8
Finger	**MPM**	**FT**	$6.1 \times 10^{-3} \times m_B \times 0.5 \times 0.6$	50.0	28.9	28.9	28.9

Table. 2-1. Inertial parameters of both conventional model and fingers model.

Palm segment was defined as from wrist joint center (WJC) to MP joint of middle finger (MPM), being the same as the hand segment in the conventional model. Finger segment was defined as from MPM to fingertip (FT). COM is referenced to proximal point (origin). Both COM and radii of gyration are relative to the respective segment lengths. These inertial properties in hand and palm segment were calculated based on previous study reported by de Leva et al, (1996) and Hirashima et al, (2002).

2.2.4 Kinematic Data

The x-, y-, and z-axes in global coordinates were set to anterior–posterior, medial–lateral, and vertical directions, respectively (Fig. 2-3). The x-, y-, and z-axes in the local coordinate system were oriented to each segment. The definition of each axis is shown in Fig. 2-3. $\mathrm{y_{fi}}$ represents a unit vector from the MP joint of the middle finger (MPM) to the fingertip; $\mathrm{x_{temp}}$ is a unit vector from MPM to the MP joint of the index finger (MPI); $\mathrm{z_{fi}}$ is the cross-product of $\mathrm{x_{temp}}$ and $\mathrm{y_{fi}}$; and $\mathrm{x_{fi}}$ is the cross-product of $\mathrm{y_{fi}}$ and $\mathrm{z_{fi}}$. In addition, $\mathrm{y_p}$ represents a unit vector from the wrist joint's center to MPM, and x_p represents a unit vector from the ulnar wrist to the radial wrist. z_p is the cross-product of x_p and y_p; y_{f0} is a unit vector from the elbow joint's center to the wrist joint's center; x_{temp2} is a unit vector from the most caudal point on the lateral epicondyle (EL) to the most caudal point on the medial epicondyle (EM); z_{f0} is the cross-product of x_{temp2}, and y_{f0}; and x_{f0} is the cross-product of y_{f0} and z_{f0}.

MATLAB (MathWorks Inc., Massachusetts, USA) was used to conduct data processing and analysis. To reduce the error of numerical differentiation, obtained positional data were smoothed using singular spectrum analysis (Alonso et al., 2005). Joint angles were calculated using the Cardan angle definition (x–y′–z″ sequence) (Winter, 2005). The rotation angle around the x-axis was defined as finger and wrist flexion/extension and that around the y-axis as forearm supination/pronation.

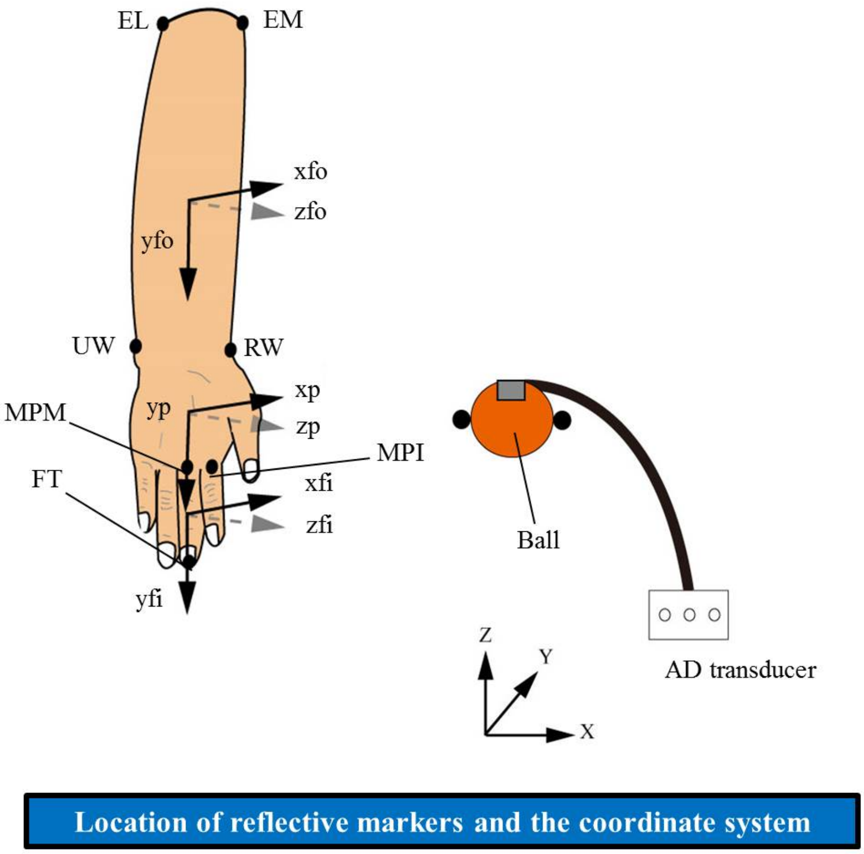


Fig. 2-3. Location of reflective markers and the definition of a coordinate system

All right-handed orthogonal systems were defined using the cross products of unit vectors by anatomical landmarks on each segment.

2.2.5 Kinetic Data

For input into the inverse dynamics model, motion analysis data were used. The position of the ball's center was estimated using the midpoint between two reflective markers on the ball. Resultant force acting on the ball was calculated from the ball's acceleration in global coordinates. The contribution of the fingers to the total force on the ball was calculated using the measurements from the force sensors. Joint torque was calculated by an inverse dynamics method (Winter, 2005) as follows:

Conventional model

$$\mathbf{T}_{\mathrm{c0}} = \mathbf{I}_0\dot{\boldsymbol{\omega}}_0 + \boldsymbol{\omega}_0\times(\mathbf{I}_0\boldsymbol{\omega}_0) + \{\mathbf{L}_{\mathrm{g0}}\times[(m_0 + m_{ball})\mathbf{a}_{\mathrm{g0}} - (m_0 + m_{ball})\mathbf{g}]\}. \quad (2\text{-}3)$$

Finger model

The equations of motion for the ball and fingers, respectively, are written as follows:

$$\mathbf{F}_{ball} + m_{ball}\mathbf{g} = m_{ball}\mathbf{a}_{ball} \quad (2\text{-}4)$$

$$\mathbf{F}_1 - \mathbf{F}_{ball} + m_1\mathbf{g} = m_1\mathbf{a}_{\mathbf{g1}} \quad (2\text{-}5)$$

$$\mathbf{T}_{\mathrm{f1}} + (-\mathbf{L}_{\mathrm{g1}})\times\mathbf{F}_1 + \boldsymbol{l}\times\mathbf{F}_{ball} = \mathbf{I}_1\dot{\boldsymbol{\omega}}_1 + \boldsymbol{\omega}_1\times(\mathbf{I}_1\boldsymbol{\omega}_1) \quad (2\text{-}6)$$

Combining these equations, the following equation is obtained.

$$\mathbf{T}_{\mathrm{f1}} = \mathbf{I}_1\dot{\boldsymbol{\omega}}_1 + \boldsymbol{\omega}_1\times(\mathbf{I}_1\boldsymbol{\omega}_1) + \left[\left(\mathbf{L}_{\mathrm{g1}}\times\left(m_{ball}\mathbf{a}_{ball} - m_{ball}\mathbf{g} + m_1\mathbf{a}_{\mathbf{g1}} - m_1\mathbf{g}\right)\right)\right] + [\boldsymbol{l}\times(-m_{ball}\mathbf{a}_{ball} + m_{ball}\mathbf{g})] \quad (2\text{-}7)$$

and

$$\mathbf{T}_{\mathrm{f0}} = \mathbf{I}_0\dot{\boldsymbol{\omega}}_0 + \boldsymbol{\omega}_0\times(\mathbf{I}_0\boldsymbol{\omega}_0) + [\mathbf{L}_{\mathrm{g0}}\times(m_0\mathbf{a}_{\mathrm{g0}} - m_0\mathbf{g})] + [\mathbf{L}_0\times(m_{ball}\mathbf{a}_{ball} - m_{ball}\mathbf{g} + m_1\mathbf{a}_{\mathbf{g1}} - m_1\mathbf{g})] + \mathbf{T}_{\mathrm{f1}}, \quad (2\text{-}8)$$

where subscripts are numbered so that a segment and its proximal joint have the same number (i = 0 for palm or wrist, i =1 for fingers or MP). $\mathbf{T}_{\mathrm{ci}}$ and $\mathbf{T}_{\mathrm{fi}}$ respectively represent the joint torque vector in the conventional and finger models. $\mathbf{I}_{\mathrm{i}}$ represents the inertia tensor of a segment. $\boldsymbol{\omega}_{\mathrm{i}}$ and $\dot{\boldsymbol{\omega}}_{\mathrm{i}}$ represent angular velocity and angular acceleration of a segment. $\mathbf{L}_{\mathrm{gi}}$ represents a vector pointing from the proximal joint to a segment's COM. $\mathbf{L}_0$ represents a vector from the wrist joint to the MP joint. $\boldsymbol{l}$ represents a vector from the finger segment's COM to the COP (fingertip) between the ball and fingers. $\mathbf{a}_{\mathrm{gi}}$ represents the acceleration vector at a segment's COM. $\mathbf{a}_{\mathrm{ball}}$ represents the acceleration vector at the ball's center. After release, the reaction force on the ball was defined as zero. $\mathbf{F}_{ball}$ represents force acting on the ball. $\mathbf{F}_1$ represents force acting on fingers. m_{ball} represents the ball's mass (0.20 kg).

Angular velocity around the y- and z-axes in the finger segment was defined as zero because there is little motion around these axes. The time of the ball's release from the index and middle fingers' tips was set as 0 ms. The power at each joint was calculated, and the work from −50 ms to REL was calculated by integrating power with time. To clarify difference in wrist joint torque between the conventional and finger models, the contribution of each term in eqs. (4) and (9) to the difference in torque between models was calculated. The value of wrist joint torque when each term in eqs. (4) and (9) is zero was compared with original wrist joint torque.

2.2.6 Sensitivity Analysis

Joint torque's reliability calculated from each model was evaluated using sensitivity analyses (Table 2-2). Both models contain some assumptions and approximations that may include errors of a few percent. The sensitivity analysis quantitatively calculates the influence of each factor's assumed error on results of basic settings. In the finger model, causes of assumed error were finger length, ball acceleration, and inertial parameter. In the conventional model, the cause of assumed error was the position of the hand segment's COM.

Finger length

A finger has three joints that can move independently: MP; proximal interphalangeal joint (PIP); and distal interphalangeal joint (DIP). In this study, however, the index, middle, and ring fingers were assumed to form one rigid body. To calculate the error in finger length, maximal variation of finger segment length (l) when throwing a ball was calculated using positional data of markers attached to the middle finger.

Ball acceleration

The assumed error of ball acceleration was determined based on previous studies (Alonso et al., 2005). Alonso et al. (2005) reported that the error between acceleration calculated from displacement and acceleration measured by the accelerometer was 2.0 $\mathrm{m/s^2}$ (about 20.0% of data in this study) at the maximum.

Inertial parameter in the finger segment

The assumed error of inertial parameter in finger segment was determined based on previous studies (Mungiole et al., 1990). Mungiole et al. (1990) reported that the difference of mass, COM, and moment of inertia between magnetic resonance imaging and mathematical methods (Hanavan, 1964) were, respectively, –6.6 %, 2.0 %, and –13.0 %.

COM of the hand segment

The cause of the conventional model's assumed error was the position of the hand segment's COM, because the ball was not considered when calculating it, although the model included the ball in the hand segment. Thus, in the conventional model, the position of the hand segment's COM was set between the wrist joint's center and the ball's center.

Table. 2-2. Results of the sensitivity analysis.

	conventional model	finger model	
	wrist flexion/extension torque	wrist flexion/extension torque	finger torque
The assumed error	**The influence that the assumed error has on the results (%)**		
Base settings	**0.000**	**0.000**	**0.000**
1. Finger length			
92 % = 100 - 8 % (the error of finger length:7.9)	**0.000**	**-0.034**	**-0.230**
2. Ball acceleration			
80 % = 100 - 20 % (the error of ball acceleration:20.0)	**0.000**	**-17.000**	**-17.000**
3. Inertial parameter in finger segment			
mass			
93 % = 100 - 7 % (the error of mass:6.6)	**0.000**	**-0.009**	**-0.110**
COM			
102 % = 100 - 2 % (the error of COM:2.0)	**0.000**	**0.480**	**0.780**
moment of inertia			
87 % = 100 - 13 % (the error of moment of inertia:13.0)	**0.000**	**-0.024**	**-0.220**
4. COM of the hand segment			
between wrist joint center and ball center	**-32.000**	**0.000**	**0.000**
			(%)

The sensitivity analysis quantitatively calculates the influence of each factor's assumed error on results of basic settings. Each value is an average value of joint torque in the total of twenty-eight throws. The influence that the assumed error of each factor has on the results of the basic settings (joint torque at -25 ms) was shown. The assumed error of inertial parameter in finger segment and ball acceleration was determined based on the previous studies (Mungiole et al, 1990; Alonso et al, 2005). Mungiole et al. (1990) reported that inertial parameter difference between magnetic resonance imaging (MRI) and mathematical methods (Hanavan, 1964) was 13 % at the max (mass: -6.6 %, COM: 2.0 %, moment of inertia: -13.0 %). Also, Alonso et al. (2005) reported that the error between acceleration calculated from displacement and acceleration measured by the accelerometer was 2.0 (about 20.0 %) at the max.

2.2.7 Statistical Analysis

Student's paired *t*-tests were used to assess significant differences following variables between the conventional and finger models: peak finger flexion torque and peak wrist flexion torque. A probability of $p < 0.05$ indicated significance. Statistical power was calculated after *t*-tests to ensure whether there were enough trials to detect statistical differences that were actually present.

2.2.8 Measurement of Force Sensor Data

COP can affect inverse dynamics calculations for fingers and wrist joints. To evaluate the validity of approximation that the COP position was located at the palmar aspect of fingertip, a uniaxial wired-force sensor (LUX-B-200N-ID-P, KYOWA ELECTRONIC INSTRUMENTS CORPORATION, Tokyo, Japan) was placed in a wooden ball (weight: 0.20 kg, diameter: 0.08 m) (Fig. 2-2B). A columnar hole (diameter: 0.02 m, depth: 0.02 m) was carved on the ball's surface, and a force sensor was fixed in the space. Raw force data were collected at 1000 Hz by the analog-digital transducer (Eagle hab 3, Motion Analysis Corp., Santa Rosa, CA, USA) and then downsampled to 200 Hz. These data were simultaneously obtained with a 3-D motion capture system. The force sensor's output showed <1% deviation from linearity for full-scale deflection over the force range recorded during this experiment.

The experiment was conducted using four force sensor locations: (1) only under the thumb's distal phalanges; (2) under both the index and middle fingers' tips; (3) under both the index and middle fingers' DIP joint; and (4) under both the index and middle finger's PIP joint. Subjects threw the ball five times in each configuration, and a trial was chosen in which the difference between all trials' average ball velocities was smallest. When the ball did not hit the target, the trial was repeated. For analysis, 28 throws at the same ball velocity were chosen from all throws (28 throws = 4 sensor locations × 7 subjects; ball velocity = 7.8 ± 0.7 m/s).

2-3. RESULTS

2.3.1 Joint Angles and Joint Torque

Participants' fingers extended until ball release and began to flex at the ball release (Fig. 2-4B). Finger torque showed flexion torque until ball release. Peak finger flexion torque was 1.8 ± 1.2 N·m. In the finger model, wrist torque showed flexion torque until ball release. Conversely, in the conventional model, wrist torque showed extension torque before ball release.

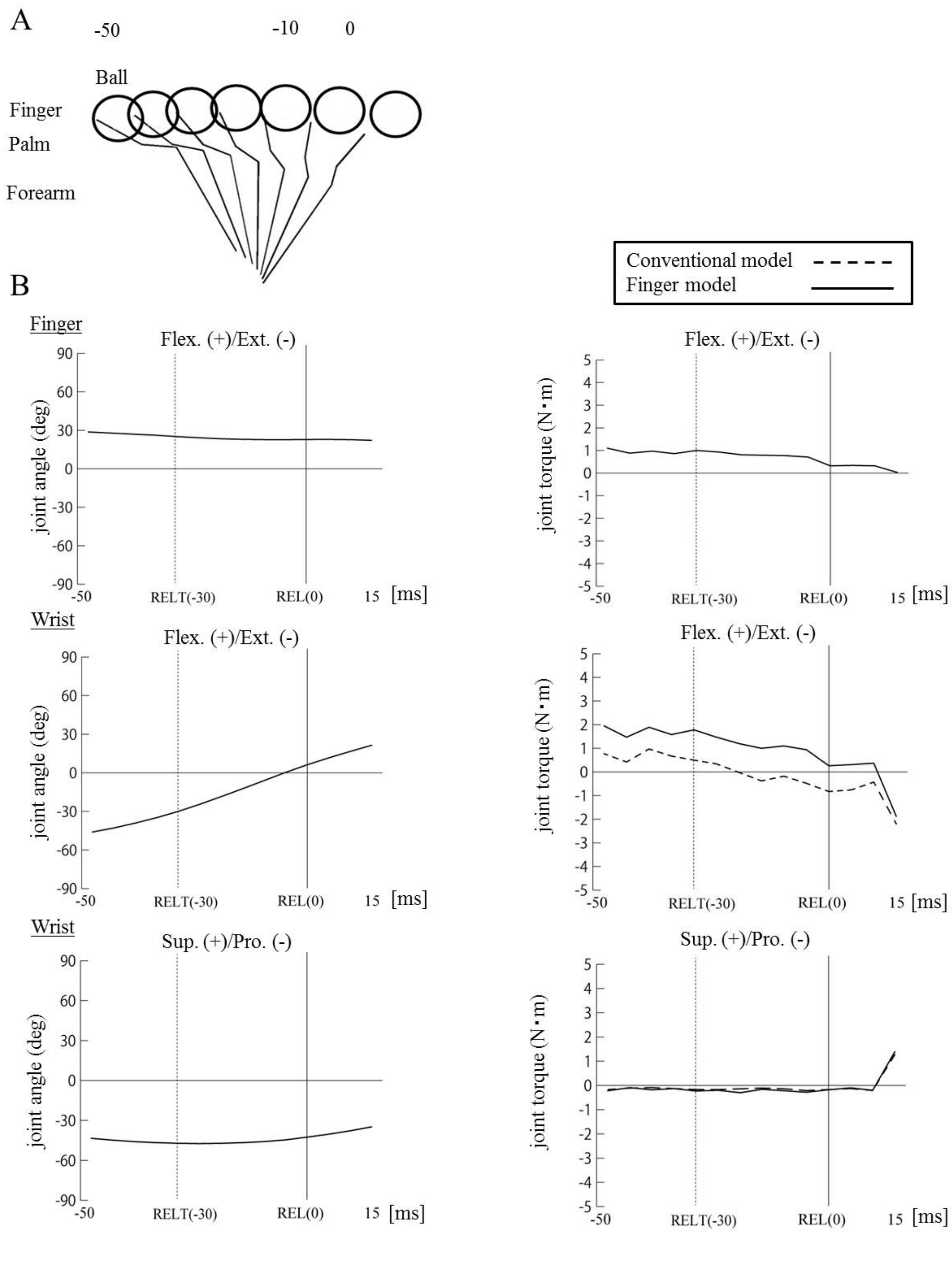


Fig. 2-4. Kinematic and kinetic data (A: stick pictures B: joint angle and torque) of each joint. Stick pictures show each segment and ball positions every 10 ms from 50 ms before ball release (REL) to 10 ms after REL. Ensemble averages (n = 28) of each joint

angle and torque. Wrist torque was computed by both models. Flex., flexion; Ext., extension; Sup., forearm supination; Pro., forearm pronation.

In the finger model, work resulting from wrist flexion/extension was significantly greater than in the conventional model ($p < 0.01$, statistical power = 0.90; Fig. 2-5). Fingers showed negative work.

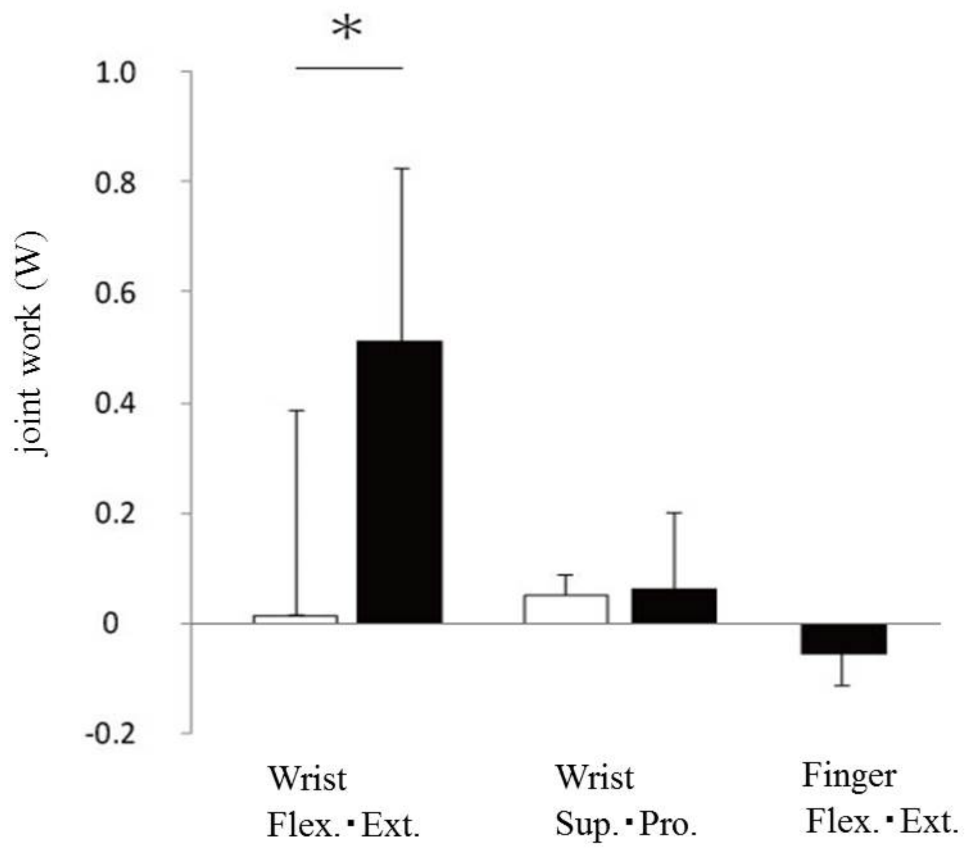


Fig. 2-5. Work computed by both models. Ensemble averages (n = 28) of work of wrist flexion/extension, forearm supination/pronation, and fingers flexion/extension for

conventional models (white) and fingers model (black) (*$p < 0.05$).

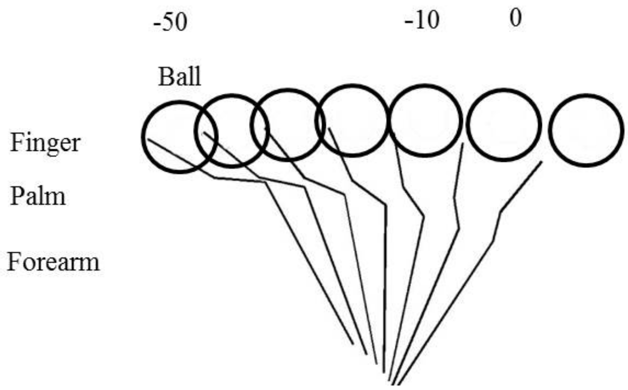
2.3.2 The Reliability of Conventional Model and Finger Model

A stick figure representation of a throw viewed from the right is shown in Fig. 2-6A. The error in finger length was 7.9 % (maximal variation of finger segment length when throwing a ball (8.65×10^{-3} m) / original length (0.11 m)) (Table. 2-2). In the conventional model, reliability of wrist flexion/extension torque was 68% $(100 - (\mathrm{COM}: 32\%))$. In the finger model, the influence of the finger length and inertia parameter's assumed errors on results of wrist flexion/extension torque was less than 1% (0.5 %). In the finger model, wrist flexion/extension torque's reliability was 82%: $(100 - [(\text{finger length and inertia parameter: } 1\ \%) + (\text{ball acceleration: } 17\ \%)])$. Similarly, in the finger model, influence of finger length and inertia parameter's assumed error on results of finger flexion/extension torque was almost equal to 0% (0.3%). In the finger model, finger flexion/extension torque's reliability was 83%: $(100-[(\text{finger length and inertia parameter: } 0\%) + (\text{ball acceleration: } 17\%)])$.

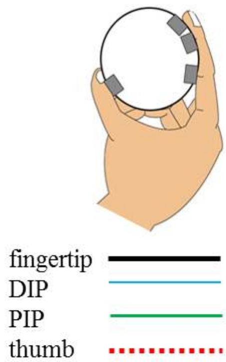
2.3.3 Force Acting on the Ball from the Fingers

Peak forces acting on the ball from thumb, fingertip, DIP, and PIP were, respectively, 5.3 ± 3.1; 5.3 ± 3.5; 3.6 ± 2.2; and 1.1 ± 1.9 N (Fig. 2-6B).

A


-50
-10
0
Ball
Finger
Palm
Forearm

B


fingertip
DIP
PIP
thumb

C

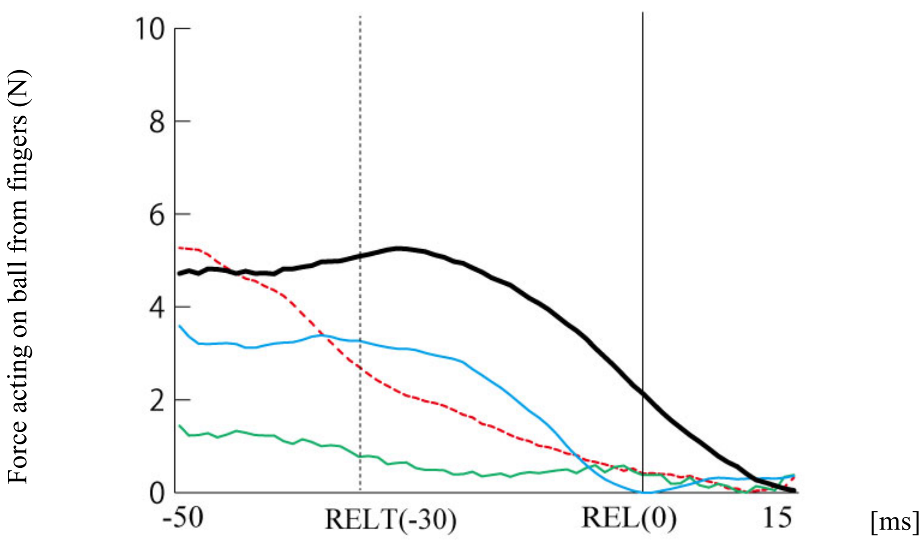
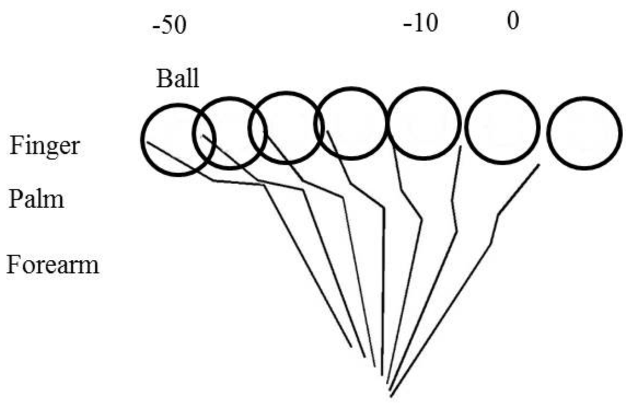

10
8
6
4
2
0
Force acting on ball from fingers (N)
-50
RELT(-30)
REL(0)
15
[ms]

Fig. 2-6. Force acting on different finger position.

Ensemble averages (n = 28) of force acting on different finger position, force acting on ball calculated from ball acceleration in global coordinate and the contribution of force acting on ball from different fingers position to the resultant force. The vertical dotted line represents the instance of ball release (REL) from the thumb (RELT) and fingertips of the first two fingers. The vertical line represents the instance of REL from a fingertip of the first two fingers. Each of force data was aligned on the moment of ball release. Seven reflective markers were attached to the subject, and two markers were attached to the wooden ball (Fig. 2-3).

Peak resultant force acting on the ball, calculated from ball acceleration in global coordinates, was 10 ± 3 N (Fig. 2-7B).

A



B

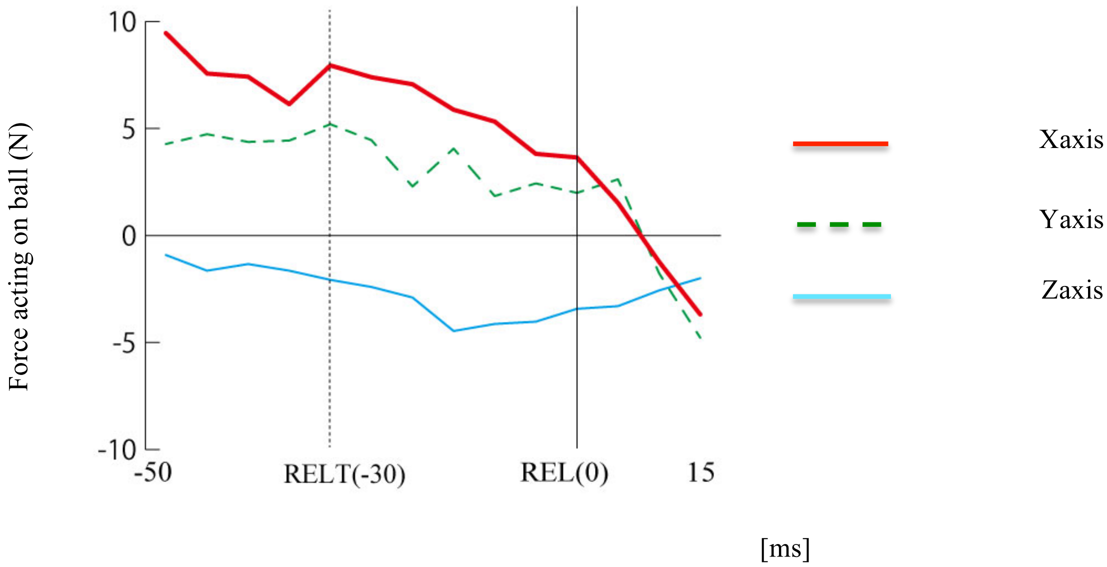


Fig. 2-7. Ensemble averages (n = 28) of force acting on ball calculated from ball acceleration in global coordinate

At −5 ms, the contribution of the fingertip to the resultant force acting on the ball, calculated from ball acceleration in global coordinates, had the highest value (60 % (Fig. 2-8)).

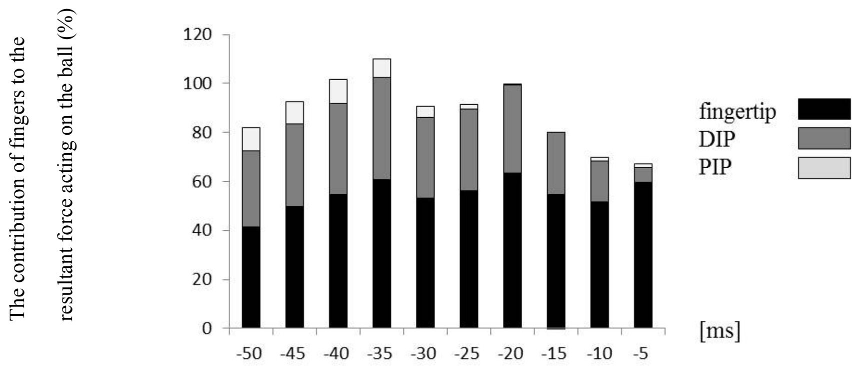


Fig. 2-8. Ensemble averages (n = 28) of the contribution of the fingertip to the resultant force acting on the ball calculated from ball acceleration in global coordinates.

2-4. DISCUSSION

2.4.1 Validation of the Finger Model

This study's first objective was to develop a link segment model considering fingers to clarify the roles of fingers torque in ball throwing. The main advantages to the fingers model are that MP joint torque can be obtained and wrist flexion/extension torque can be calculated more accurate than the conventional model. This suggests that it is effective to apply this method for clarifying the roles of fingers torque and wrist torque to ball rotation and accuracy in ball throwing. It was also advantages to this method that new hardware and many changes of analysis program are not required, since only one segment is added to existing technique.

From the sensitivity analysis, it was revealed that the reliability of MP joint torque in the fingers model was 83 %, and it was mainly affected by ball acceleration. This error is not a inherent problem in this method, but merely a problem of measurement precision. By improving only measurement precision of ball acceleration, the reliability can be 99 % at the maximum. The finger length error was 7.9%, but the influence of finger length error on finger torque was quite low (0.2%). If spatial resolution in motion capture system is improved, this error decreases because it can be improved to 1 mm or less (catalogue value). This result indicates that the assumption of finger segment forming one rigid body is reasonable. Additionally, finger mass was estimated on general regression, although subjects were a special population (baseball players). In the finger model, the influence of the assumed error of finger length and inertia parameter on results of wrist and finger flexion/extension torque was less than 1%. Also, Yokoi et al. (1998) studied the effects of body segment inertia parameter (athlete or general adult) on results of kinematic and kinetic analysis of human movement. This study revealed that selection of body segment parameter apparently has little effect on results of biomechanical analysis. This result is similar to present study's result and supports the validity of estimation of finger mass. Therefore, use of the general regression model is not a problem. Additionally, fingers' kinematics was consistent with the result reported by Hore et al. (1996c). These results support the validity of the finger segment's setting.

Force acting on the ball at the fingertips was always greatest of those at the three finger locations, i.e., fingertip, DIP, and PIP (Fig. 2-4). Especially, peak forces acting on the ball at the fingertip and DIP, which is close to the fingertip, were large values. Additionally, force acting at the PIP was small. These results likely confirm that the COP's position was valid. However, in fact, the COP will move because the ball rolls finger. To develop further detailed finger model, future study will need to estimate a moving COP instead of placing the COP at the fingertip.

Sum of fingers force measured using the sensor buried in the ball should be equal to the reaction force calculated from the center of ball's acceleration according to the Newton's third law of motion. The average value of the total amount of contribution of fingertip, DIP, and PIP to the resultant force acting on the ball calculated from ball acceleration in global coordinates was $89 \pm 14\%$. Probably, the remaining force is due to force acting parallel to the surface of the ball (shear force). The uniaxial (1-dof) force sensor used in the present study can only measure the force perpendicular to the surface of the sensor. Future study will need to record the contact force vectors with 3-dof force sensors.

In this study, force acting on the ball from PIP and DIP decreased in the ball release's latter stage as the ball rolled off the fingers (Fig. 2-4). Additionally, force acting on the ball from fingertips increased in the latter stage of ball release. In contrast, Hore et al. (2001) found increased force acting on PIP and DIP in the latter stage of ball release when measured by a force transducer on a finger. A likely reason for the difference between the previous study and this study was the grip on the ball. In Hore et al.'s (2001) study, the whole hand gripped the ball when throwing balls larger than a tennis ball (diameter: 0.065 m). In this study, subjects gripped the ball with the first two fingers and thumb and, additionally, with a gap between the ball and the hand. Thus, with the latter grip, force acting on the ball from PIP and DIP would decrease, and force acting on the ball from fingertips would increase in the latter stage of ball release. Overall, these results support the validity of force sensor data.

In this study, force acting on ball calculated from ball acceleration in global coordinate was not zero after complete release. Probably, this is due to the error of ball center. In this study, the position of the ball's center was estimated using the midpoint between two reflective markers on the ball. If the estimated position of ball center is deviates, the position includes centrifugal force by ball rotation. As a result, this leads to the error of finger model. However, the centrifugal force ($m\frac{v^2}{r}$) would be small because ball velocity in this study was very low. Thus, the error of ball center was not a critical problem for calculating finger torque.

2.4.2 Difference between the Conventional and Finger Models

This study's second objective was to reveal the wrist joint torque's difference between the conventional model and the finger model in which the finger segment was considered rigid. The reliability of wrist flexion/extension torque in the fingers model is improved by 14 % $((\text{fingers model: } 82\ \%) - (\text{conventional model: } 68\ \%))$ than the conventional model. Specifically, the reliability in the conventional model was mainly affected by the position of COM of the hand segment. In the finger model, wrist torque showed flexion torque before ball release. However, this result differed from those of previous studies, which used the conventional model for calculation (Hirashima et al., 2008; Debicki et al., 2011). In the conventional model, wrist flexion torque was smaller than that of the finger model. Additionally in the conventional model, before ball release, wrist torque showed extension torque. This is large difference on discussing the biomechanical role of wrist during ball throwing. The main reason for this difference was measuring acceleration at the ball's center ($\mathbf{a}_{\text{ball}}$). From eqs. (4) and (9), the contribution of each term in the equation to the difference in torque from both models was calculated. The contribution of acceleration at the ball's center was the largest of all terms ($\mathbf{a}_{\text{ball}}$: 84%, $\mathbf{a}_{\mathbf{g1}}$ (acceleration of fingers): 5%, $\mathbf{g}$ (gravity acting on fingers): 4%). From these results, in discussing not only the function of finger motion during aimed throwing, but also the function of wrist motion, applying a link-segment model considering the fingers might be necessary. At the same time, these results suggest that it is possible to improve the reliability of wrist flexion/extension torque in the conventional model by considering ball position.

The large standard deviations were presented in the results of this study, which indicates that there is a great deal of inter-pitcher variability. Especially, work at wrist flexion/extension varied from pitcher to pitcher. Solomito et al. (2014) suggested that large standard deviation of pitcher's motion could be indicative of different styles of coaching experienced by the pitchers involved in this study when learning how to use wrist during ball throwing. In fact, it was reported that there were large standard deviation of peak wrist flexion torque (12.6± 5.6 Nm) for baseball pitching (Solomito et al., 2014). Thus, these results also support the validity of wrist kinetic data.

2-5. Summary of Chapter 2

This study had two objectives: (1) developing a link segment model considering fingers to clarify the roles of fingers torque in ball throwing and (2) revealing the wrist joint torque's difference between the conventional model and the finger model in which the finger segment was considered rigid. Using the fingers model, specifically, two findings were revealed: (1) MP joint torque can be obtained and (2) wrist flexion/extension torque can be calculated more accurate than the conventional model. The reliability of MP joint torque in the fingers model was 83 %. It was mainly affected by ball acceleration (-17 %). The reliability of wrist flexion/extension torque in the fingers model is improved by 14 % than the conventional model. It was mainly affected due to the ball position's approximation error. This suggests that it is possible to improve the reliability in the conventional model by considering the ball position.

CHAPTER 3

Timing Control Between Wrist Torque And Finger Torque During Ball Throwing

3-1. Introduction

In chapter 2, fingers model during ball throwing was developed, and its validity was verified. Some previous studies have investigated fingers' movement timing (e.g., Hore et al., 1996a; Hore et al., 2011). Hore et al. (1996a) reported that finger extension's timing is more important for an accurate overarm throw than rotation onset timing at a more proximal joint. Hore et al. (2011) also reported that skilled throwers achieve accuracy in overarm throwing by computing finger force/stiffness with timing precision as low as 1 ms. In summary, finger movement's timing is a significant factor in achieving accurate ball release.

In ball throwing, the proximal-to-distal segmental sequence (P–D sequence) was identified by Pappas et al. (1985) and Feltner (1989), who considered the segmental sequence essential for effective generation of great speed in the distal segment. Hirashima et al. (2002) reported that sequential muscle activity from shoulder horizontal flexors to the elbow extensor was identified by each peak time. However, whether P–D sequence from wrist to finger occurs was not examined. Thus, this study's objective was to examine the central nervous system's (CNS's) timing control between wrist torque and finger torque. Probably, for accelerating the ball further, the P–D sequence would also occur at more distal segment. Hirashima et al. (2008) indicated that the timing of peak wrist flexion torque occurred at near 50 ms before ball release. Thus, the timing of peak finger flexion torque was anticipated to be significantly later than 50 ms before ball release (the timing of peak wrist flexion torque) for further accelerating the ball.

3-2. Methods

3.2.1 Experimental Design and Data Collection

Experimental tasks were same as Chapter 2 (see 2.2.1 for detail explanation of the experimental design). Also, the positional data of the markers attached to the subjects and the ball were used in this chapter as well.

3.2.2 Data Analysis

Based on finger model (see 2.2.3 for detail explanation of the finger model), kinematics and kinetics of fingers was calculated. The timings of peak wrist and finger flexion torque relative to ball release were determined.

3.2.3 Cross-Correlation Analysis

To examine similarity between wrist joint torque and finger joint torque, a cross-correlation function was used. The data from −50 ms to REL were kept for analysis. The data series of wrist joint torque (n = 28) was cross-correlated with the data series of finger joint torque (n=28). The maximal correlation coefficient and the time lag were calculated. Cross-correlation between pairs of processed torque curves was performed as follows. Consider two series x_i and y_i where $i =$ 0, 1, 2, ⋯, N-1. The normalized cross-correlation function with zero time lag is calculated, with N=10, as

$$R = \frac{\sum x_i y_i}{\left(\sum x_i^2\right)^{1/2}\left(\sum y_i^2\right)^{1/2}} \qquad (3\text{-}1)$$

3.2.4 Statistical Analysis

Difference between the timing of peak finger flexion torque and peak wrist flexion torque was also analyzed using student's *t*-tests. A probability of $p < 0.05$ indicated significance.

3-3. RESULTS

In cross-correlation analysis of the finger model, the maximal correlation coefficient between wrist joint torque and finger joint torque was very high ($r = 0.85 \pm 0.10$; Fig. 3-1). The time lag at maximal correlation coefficient was very small ($t = 0.36 \pm 3.0$ ms), and this lag did not differ significantly from 0.

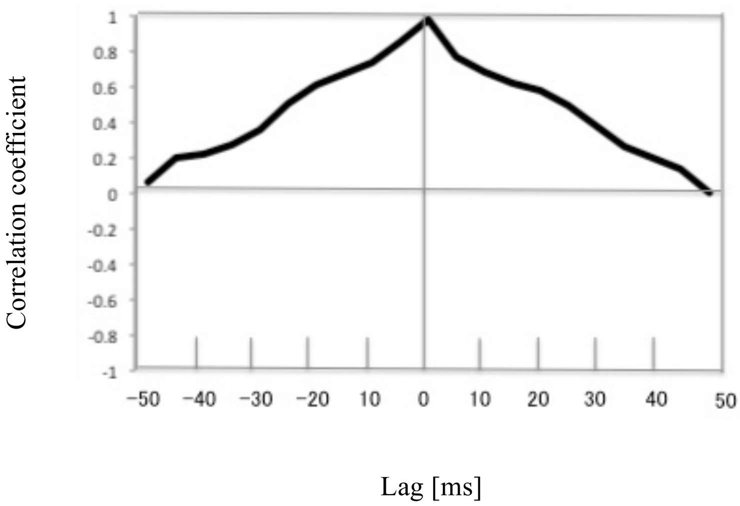


Fig. 3-1. A representative result of the cross correlation function between wrist joint torque and finger joint torque.

There were no significant differences between timing of peak finger flexion torque (–34 ± 16 ms) and peak wrist flexion torque (–43 ± 8 ms) (Fig. 3-2).

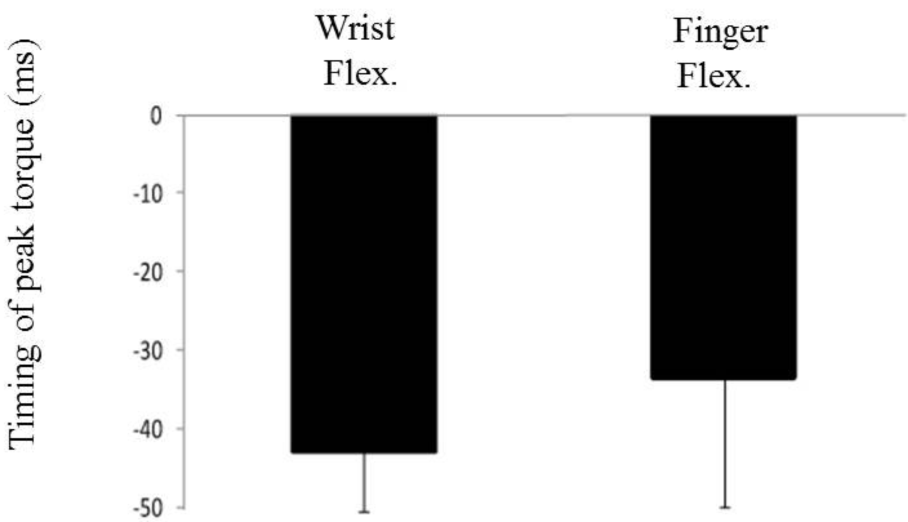


Fig. 3-2. The timing of peak flexion torque relative to ball release. Ensemble averages (n = 28) of timing of peak wrist and finger flexion torque (*$p < 0.05$). Student's paired *t*-tests were used to assess significant differences following variables between the conventional and finger models: peak finger flexion torque and peak wrist flexion torque.

3-4. DISCUSSION

3.4.1 Control of Wrist and Fingers Flexors during Ball Throwing

This study's objective was to examine the timing control between wrist torque and finger torque. However, results showed no significant differences between timing of peak finger flexion torque (–34 ± 16 ms) and peak wrist flexion torque (–43 ± 8 ms). This result differs from the hypothesis that the timing of peak finger flexion torque would be significantly later for further accelerating the ball than the timing of peak wrist flexion torque. It was considered that the main reason for the similarity between the timing of peak finger flexion torque and peak wrist flexion torque was due to extrinsic finger muscles' anatomical arrangement. Werremeyer and Cole (1997) showed that voluntary wrist motion affects the precision of grip force because extrinsic finger muscles cross the wrist. They found that during wrist flexion movement when grasping an object, the timing of initial peak in grip force coincided roughly with the timing of peak wrist acceleration. They explained that extrinsic finger flexors (i.e., flexor digitorum superficialis) were recruited to assist the intended wrist action. This seems to have added drive to wrist flexors (i.e., flexor carpi radialis) to overcome any loss in muscle force, whereas extrinsic finger flexors shortened during wrist flexion motion (Werremeyer and Cole, 1997). Likewise, when throwing a ball, the wrist flexed rapidly before ball release when grasping the ball. Therefore, the timing of peak finger flexion torque was anticipated to coincide roughly with the timing of peak wrist flexion torque. These results seem to demonstrate that the main reason for similarity in peak torque timing is due to extrinsic finger muscles' anatomical arrangement.

3.4.2 Timing Control of Wrist and Fingers

The CNS must take into account the body segment's mechanical properties to execute desired movements (Bernstein 1967, 1996). Of arm segments, the elbow joint is kinematically and dynamically advantageous for adjusting ball-throwing velocity because the forearm is long and more massively muscular than distal segments (Putnam, 1991). In addition, Hirashima et al. (2002) reported that sequential muscle activity from shoulder horizontal flexors to the elbow extensor was identified by peak time. These results indicate that the CNS made the elbow joint contribute to adjusting ball speed. In contrast, the wrist and fingers are smaller segments with less musculature than the elbow (Ajiri, 1981; Teratani et al., 1984). This study revealed no significant differences between the timing of peak finger flexion torque and peak wrist flexion torque. Ball-throwing motion requires not only adjustment of ball speed, but also of accuracy. Several studies have shown that release timing's precise control is the most important factor for accurate throwing (e.g., Hore et al., 1996a; Chowdhary and Challis, 1999). Hore et al. (1996a) reported that finger extension timing with respect to the wrist is important for accurate ball throwing. In fact, a 1-ms delay in fingers' extension causes a 2.2-degree change in the ball's direction. The simulation study has also suggested that throwers need to release within a window as short as 1 ms to hit a target 20 cm in diameter positioned further than 6 m (Chowdhary and Challis, 1999). Thus, if a few milliseconds' delay between wrist torque and fingers' torque occurs, ball trajectory changes significantly. In this study, synchronization of wrist torque and fingers torque was found (no significant delay of peak finger flexion torque). During rapid throwing motion, adjusting grip force according to ball acceleration to keep gripping the ball is necessary. Throwing movements are too fast to make corrections based on proprioceptive information (Cordo et al., 1994). That is, when a human throws a ball, online feedback is not feasible (Hirashima et al., 2003a). If the timing of peak finger flexion torque follows the timing of peak wrist flexion torque later, through online feedback, a ball would slip on the fingers before optimal release due to feedback delay. Fingers' torque can be viewed as a consequence of feed-forward control (Ambike et al., 2013). The time lag at the maximal correlation coefficient was 0.36 ± 3.02 ms, but temporal resolution in this study was 5 ms (200 Hz). From these results, to stabilize release timing, the wrist torque and fingers' torque seems to have been synchronized wrist torque and fingers' torque by feed-forward control within a window as short as 5 ms. In this study, on the other hand, wrist torque (−43 ± 8 ms) and finger torque (−34 ± 16 ms) showed some timing variability. As Newell and Corcos (1993) stated, "Variability is inherent within and between all biological systems." Thus, trial-to-trial variability has been observed in human behavior because noise exists at all levels of the nervous system (Nasu et al., 2014). Müller and Loosch (1999) suggested that because timing variability cannot be completely eliminated, intrinsic timing variability can be compensated for by modifying hand trajectory. Therefore, throwers are likely optimize their hand trajectory to compensate for intrinsic timing variability of wrist torque and finger torque.

3.4.3 Limitations

This study has several limitations. First, ball velocity was restricted (7.8 ± 0.7 m /s) so that the infrared camera could capture finger motion accurately. Hore et al. (2001)

reported that fast throws had greater forces acting on the fingertips than slower throws. Therefore, when throwing a ball, finger flexion torque is expected to increase in proportion to ball velocity. Future studies will need to focus on finger flexion torque's function at different ball velocities. Examining kinetic and temporal parameters during ball throwing, Solomito et al. (2014) found that the timing of peak wrist flexion torque occurred during the latter portion of the throwing cycle (time between the maximum external rotation of shoulder and the instant of ball release). Although ball velocity in this study (7.8 ± 0.7 m/s) was lower than that of the previous study (33 ± 2 m/s), the timing of peak wrist flexion torque in this study approximates that of the previous study. In addition, Urbin et al. (2012) examined ball velocity-accuracy trade-off in overarm throwing with novices and experts. They reported that no trade-off between velocity (range of mean ball velocity from 8.4 m/s to 33 m/s) and accuracy was found for novices or experts. These results show that there is no large influence because the conclusion on timing data and accuracy in this study was not changed by the limitation of ball velocity.

The second limitation in this study is that throwing distance was restricted (2.7 m) because of the laboratory study. However, the distance is the same as that in a previous study (Hirashima et al., 2003a) focused on arm kinetics' general features during aimed throwing. Watts et al. (2004) reported that ball release timing did not change by the distance if ball speeds are constant. Thus, even if the throwing distance is long, the timing of peak finger torque is anticipated to be the same as that in this study, indicating that distance limitation was not critical to the analysis of timing data. However, for obtaining detailed knowledge about accuracy in overarm throwing, future studies will need to focus on finger kinetics at different heights and distances.

The third limitation in this study is that temporal resolution was 5 ms (200 Hz). However, the time lag at the maximal correlation coefficient was 0.36 ± 3.02 ms. Thus, from present study, it was concluded that throwers control wrist torque and finger torque within a window as short as 5 ms.

3-5. Summary of Chapter 3

This study's objective was to examine the central nervous system's timing control between wrist torque and finger torque. The maximal correlation coefficient between wrist joint torque and finger joint torque was very high (r = 0.85 ± 0.10), and the time lag at the maximal correlation coefficient was very small (t = 0.36 ± 3.02 ms). A little delay in timing between wrist torque and fingers' torque greatly influences ball trajectory. From these results, to stabilize release timing, the CNS seems to synchronize wrist torque and fingers' torque by feed-forward adjustments.

CHAPTER 4

CONTROL OF FINGERS TORQUE DURING BALL THROWING UNDER DIFFERENT BALL VELOCITY

4-1. Introduction

In chapter 2, fingers torque could be quantified (peak finger flexion torque: 1.8 ± 1.2 N·m). However, it was not clear how much the relative value of finger flexion torque when throwing a ball is. Also, in chapter 2, it was anticipated that the CNS made the synchronization of wrist torque and fingers torque by feed-forward adjustments to stabilize release timing. In baseball, pitchers throw a ball with wide range of ball velocity keeping accuracy. However, ball velocities analyzed in Chapter 2 were slow (7.8 ± 0.7 m/s) , and it was restricted. Hence, it was questioned if the role of wrist torque and fingers torque during ball throwing was the same under different ball velocities (slow, medium, fast).

Force performed through joint changes according to joint angle. Hashihara (1987) investigated the static strength exerted at the different joint angles of the shoulder, elbow and wrist. They indicated that the maximum flexion strength for each subject was obtained in the range from 50 to 140 degree in the shoulder, 80 to 100 degree in the elbow, and -70 to 10 degree in the wrist. However, the static strength exerted at the different joint angles of MP joint was not measured, and there is no study that examines the force in association with ball throwing.

Also, many studies have examined force-velocity relationship at elbow joint (e.g. Toji and Kaneko, 2007; Valour et al., 2003). However, there is few study about eccentric contraction, and no studies have revealed force-velocity relationship during fingers flexion movement.

It has previously been shown (Hore et al., 2001) that fast throws generate larger grip force than slow throws. Thus, it was expected that kinetic parameters (joint torque and work) of wrist and fingers during fast throws was larger than slow throws. That is, it was considered that wrist and fingers joint contribute to adjusting the ball velocity under fast throws.

It was hypothesized that the maximum isometric flexion torque at fingers joint will be also in the range of that of wrist joint (-70 to 10 degree in the wrist) reported by previous study (Hashihara et al., 1987) because the extrinsic finger muscles cross the wrist. Also, in the torque–angular velocity relationship, the concentric torque decreased with increasing velocity (e.g., Westing et al., 1988; Valour et al., 2003.) It is anticipated that fingers joint will be similar to the results for other joints reported in these previous studies.

The first objective in this study was to examine the biomechanical role of wrist and fingers torque under different ball velocity. A second objective in this study was to evaluate the percentage of finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque.

4-2. Methods

4.2.1 Experimental Design

Six healthy male subjects (age: 26 ± 4 years, mass: 73 ± 9 kg, height: 1.79 ± 0.06 m) participated in the experiment with informed consent. They were right-handed baseball players (mean baseball experience: 6 ± 4 years). All subjects were instructed to stand with their left foot forward and right toe contacting the ground during aimed throwing. They threw the ball with overarm throw toward a target made of cloth. The subjects gripped the ball with the first two fingers and thumb. Additionally, they griped the ball spacing at a gap between the ball and hand. The size of the target was 0.6 m × 0.6 m. The horizontal distance between the target and left foot was 3.5 m, and the height of the center of the target was set at eye-level. The target surroundings were covered with a safety net and mat.

Throws were made under three different velocity conditions: "slow-accurate," "medium-accurate," and "fast-accurate." Each of three conditions was randomly presented once to construct one bout, and five bouts were repeated. Thus, the subjects threw the ball five times in each configuration. Each subjects made a total of 15 throws. When the ball did not hit the target, the trial was repeated.

4.2.2 Recording Movement

Seven reflective markers were attached to the subject and four markers were attached to the baseball. The markers on the fingers were 14 mm in diameter, and the others (palm, forearm and a ball) were 19 mm in diameter. Motions were recorded at a sampling rate of 200 Hz using a 3D motion analysis system (HAWK Digital System, Motion Analysis Corp., Santa Rosa, CA, USA). The instants of ball release from thumb (RELT) and fingertips of the first two fingers (REL) were obtained by high speed camera at 1000 fps (MEMRECAM HX-6, nac Image Technology Inc., Tokyo, Japan).

4.2.3 Finger Model

Based on finger model (see 2.2.3 for detail explanation of the finger model), kinematics and kinetics of fingers was calculated. Some mass parameters of the palm segment were modified. In Chapter 2, the mass of the palm segment (m_P) was set as follows:

$m_P = 6.1\times10^{-3}\times m_B$

(4-1)

where m_B is the mass of body, 6.1×10^{-3} is the hand to body mass ratio (de Leva et al., 1996). However, the body mass ratio (0.61 %) of the hand in the paper included the mass of the palm and five fingers. Therefore, 6.1×10^{-3} should be divided by two for the palm. In addition, the mass of the remaining two fingers (thumb and little finger) should be added to palm. Thus, the mass of the palm segment (m_P) was modified as follows:

$$m_P = 6.1\times10^{-3}\times m_B\times0.5\times(1 + 0.4) \quad (4\text{-}2)$$

where 0.4 implies that the mass of the remaining two fingers is added to the palm. Also, the COM value of 79.0 % (de Leva et al., 1996) cannot be directly used for the palm, because 79.0 % of the hand segment in the paper was calculated based on the length from the wrist joint to the third MP joint. Thus, the center of mass in the palm segment (COM_P) was modified as follows:

$$COM_H = \frac{(0.3\times m_H\times COM_F)+(0.7\times m_H\times COM_P)}{m_H}$$

(4-3)

From this equation, a follow equation is obtained.

$$COM_P = \frac{10COM_H - 3COM_F}{7}$$

(4-4)

COM_H represents longitudinal COM position of hand segment (de Leva et al., 1996). m_H is hand's total mass. 0.3 implies that finger's mass is 30 % of the hand's total mass (see 2.2.3 for detail explanation of the finger model), and 0.7 implies that palm's mass is 70 % of the hand's total mass. Radius of gyration in the palm segment was set as 50 % of the hand. The power at each joint was calculated, and the work from −50 ms to REL was calculated by integrating the power with respect to time.

4.2.4 Estimation of Moving COP

The center of pressure (COP) of the ball is going to dramatically affect inverse dynamics calculations for the finger and wrist joints. In Chapter 2, the COP in finger model was placed at fingertip. To develop further detailed finger model, we estimated the position of moving COP. The COP between the ball and the fingers was calculated using the force acting on the ball from fingertip, DIP, and PIP as follows.

$$COP_F = \frac{(F_f \times l_f) + (F_{DIP} \times l_{DIP}) + (F_{PIP} \times l_{PIP})}{F_f + F_{DIP} + F_{PIP}} \quad (4\text{-}5)$$

COP_F represents length from MP joint in middle finger to the position of COP in finger segment. F_{f}, F_{DIP} and F_{PIP} respectively represent the force acting on the ball from fingertip, DIP, and PIP. The data of force acting on the ball from fingers measured in Chapter 2 was used. l_{f} is length from MP joint to fingertip in middle finger. Also, l_{DIP}

and l_{PIP} are length from MP joint to DIP and PIP joint. l_{DIP} and l_{PIP} are calculated from distal and medial phalange bone lengths reported by previous study (Kong et al., 2016). The mean of the data of seven subjects were used for input into the inverse dynamics model.

4.2.5 Kinematic Data

The x-, y-, and z-axis in global coordinates were set to anterior–posterior, medial–lateral, and vertical directions, respectively (Fig. 2-3). The x-, y-, and z-axis in the local coordinate system were oriented to each segment. The x-, y-, and z-axis in the global and local coordinates system were same as Chapter 2 (see 2.2.4 for detail explanation of the kinematic data).

MATLAB (MathWorks inc., Massachusetts, USA) was used to conduct data processing and analysis. The data from −50 ms to REL was kept for analysis. To reduce the noise of positional data , the obtained positional data were smoothed using singular spectrum analysis (Alonso et al., 2004). The instantaneous position of the ball center was estimated from the coordinates of the four reflective markers on the ball using the least-square technique, the position is equidistant from each marker. The ball spin rate immediately after ball release was calculated from the four reflective markers attached to the pitched baseball using the methods described by Jinji and Sakurai (2006). Joint angles were calculated using the Cardan angle definition (x–y′–z″ sequence) (Winter, 2005). The rotation angle around the x-axis was defined as finger and wrist flexion/extension and that around the y-axis as forearm supination/pronation.

4.2.6 Kinetic Data

Using finger model (see 2.2.5. for detail explanation of the finger model), kinetics of fingers (torque, power and work) was calculated. The power at each joint was calculated, and the work from −50 ms to REL was calculated by integrating the power with respect to time.

4.2.7 Torque-Angle Relationship

4.2.7.1 Experimental design

To evaluate the percentage of finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque, the torque–angle relationship and torque–angular velocity relationship of a subject's fingers were examined. A right-handed healthy male subject (age: 28 years, mass: 58 kg, height: 1.68 m) participated in the experiment with informed consent.

The position of measurement in torque-angle relationship was shown in Fig. 4-1A. The PIP and DIP joint of index finger and middle finger was neutral position, and a stainless steel board was fixed on these fingers with surgical tape and strap. The subject was tested in a sitting position and the elbow was in a full extension position. Also, the forearm was full supination position, and the wrist in the neutral position. The forearm and palm was fixed on the table with the strap. Assuming baseball throwing, thumb, ring finger, and little finger were flexed lightly. The torque–angle relationship was measured isometrically at different MP joint angles of −20, 0, 20, 40, 60, and 80 degrees. Subjects were instructed to produce the maximum isometric flexion torque for two seconds. Two trials at each condition were performed randomly. A 1-minute rest period was provided between two consecutive trials to counter the effects of fatigue.

4.2.7.2 Recording movement

Three reflective markers were attached to the subject and two markers were attached to the tip of stainless steel board and wire (Fig. 4-1B).

A

B

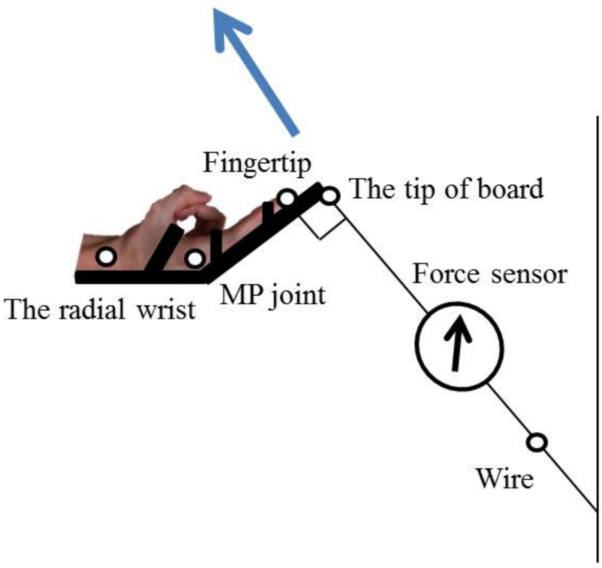


Fig. 4-1. A: The fix method of fingers and B: the position of measurement of the maximum isometric force at MP joint

The markers on the fingers were 14 mm in diameter, and the others (the radial wrist, the tip of board and wire) were 19 mm in diameter. Motions were recorded at a sampling rate of 200 Hz using a 3D motion analysis system (HAWK Digital System, Motion Analysis Corp., Santa Rosa, CA, USA). To measure the maximum isometric force at MP joint, a uniaxial wired-force sensor (LUX-B-50N-ID-P, KYOWA ELECTRONIC INSTRUMENTS CORPORATION, Tokyo, Japan) was used. The force sensor was fitted up with wire, and angle between the wire and the stainless steel board were adjusted to be vertical angle. If angle between the wire and the stainless steel board were not vertical angle, the perpendicular force to fingers was corrected based on angle between the wire and the stainless steel board calculated from motion capture data. Raw force data were collected at 1000 Hz by analog-digital (AD) transducer (Eagle hab 3, Motion Analysis Corp., Santa Rosa, CA, USA). These data were simultaneously obtained with a 3-D motion capture system.

4.2.7.3 Kinematic and kinetic data

MATLAB (MathWorks inc., Massachusetts, USA) was used to conduct data processing and analysis. To reduce the noise of positional data, the obtained positional data were smoothed using singular spectrum analysis (Alonso et al., 2005). MP joint angle (flexion/extension) was calculated using the positional data of markers attached to the index finger and the radial wrist. From times series data of joint angle and force, the range that force for 0.5 s was max was chosen as analysis period (Fig. 4-2). Joint angle and force are recorded immediately after examiner instructed the subject to perform. 0 ms represents the beginning of record.

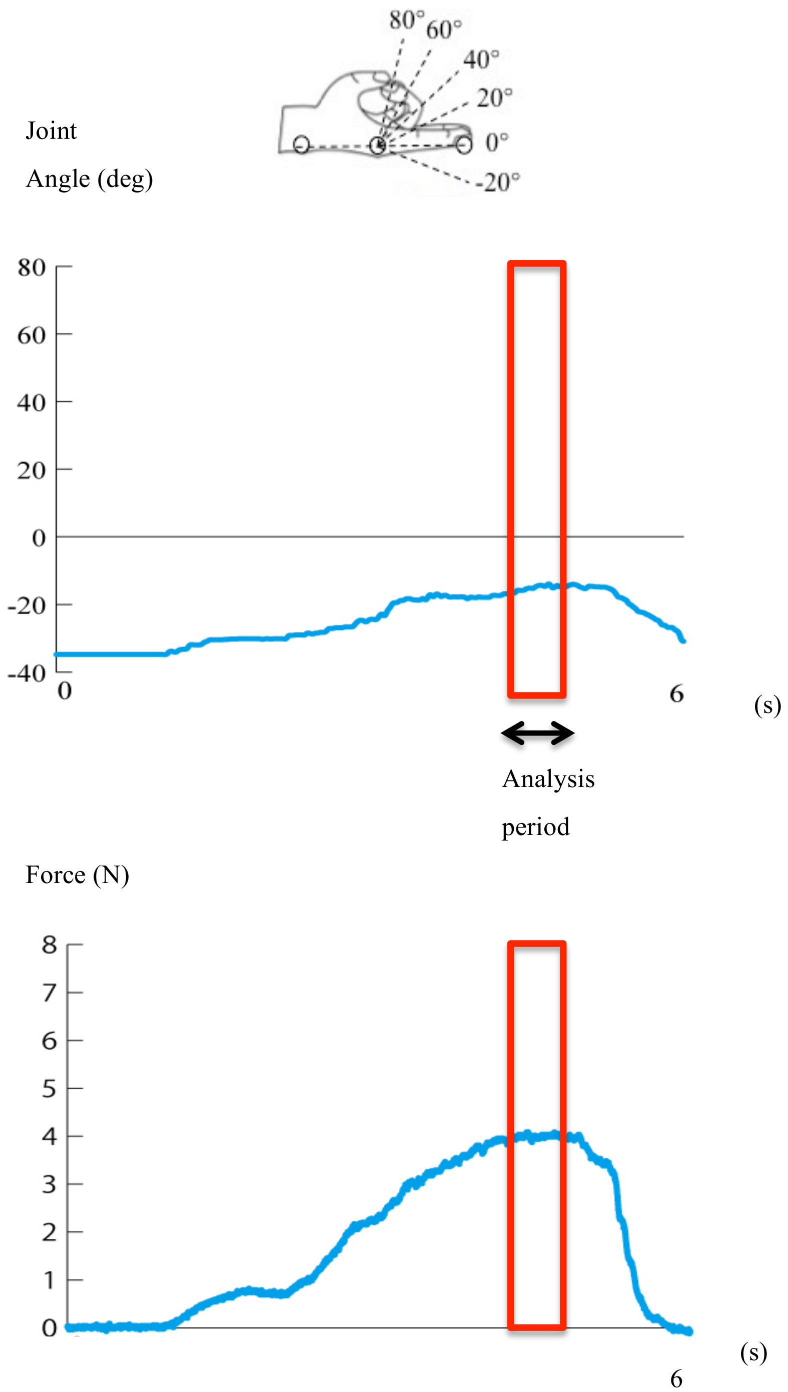


Fig. 4-2. The time series of MP joint angle of -20 degrees and isometric force.

From times series data of joint angle and force, the range that force for 0.5 s was max was chosen as analysis period. 0 ms represents the beginning of record.

The subjects performed two trials at each test angle, and the trial that force is larger was selected. The isometric finger flexion torque was defined as the recorded finger force multiplied by the MP joint axis to the point of application of that force.

4.2.8 Torque-Angular Velocity Relationship

4.2.8.1 Experimental design

The concentric and eccentric torque–angular velocity relationship was measured isokinetically at different loads. The position of measurement in torque-angular velocity relationship was the same as torque-angle relationship. The load of 500 g at each trial was added from unloaded condition (Fig. 4-3).

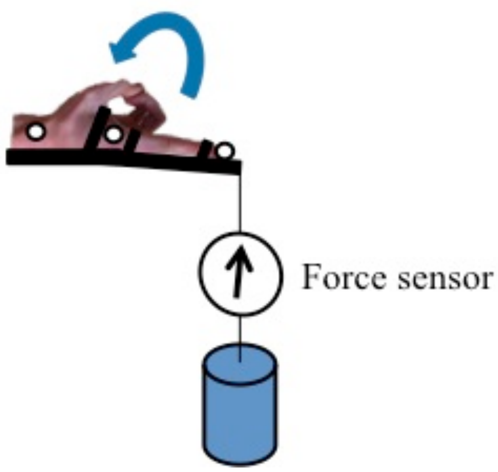


Fig. 4-3. The experimental set of the torque-angular velocity relationship at MP joint

Subjects were instructed to flex their MP joint from maximal extension position at maximum effort throughout the entire range of motion. From 30 to 60 seconds rest period was provided between two consecutive trials to counter the effects of fatigue. Also, from 3 to 5 minutes rest period was provided between the first half series and second half series.

We added the load subjects could not lift to 500 g, and this was the condition at eccentric contraction. First, a examiner supported the load by the hand, the subject kept MP joint angle about 45 degrees. Second, the examiner released the hand he supported softly. Subjects were instructed to flex their MP joint at maximum effort for resisting finger extension by loads.

4.2.7.2 Recording movement

Three reflective markers were attached to the subject. The markers on the fingers were 14 mm in diameter, and the radial wrist was 19 mm in diameter. Motions were recorded at a sampling rate of 200 Hz using a 3D motion analysis system (HAWK Digital System, Motion Analysis Corp., Santa Rosa, CA, USA). To measurement force at MP joint, a uniaxial wired-force sensor (LUX-B-50N-ID-P, KYOWA ELECTRONIC INSTRUMENTS CORPORATION, Tokyo, Japan) was used. The force sensor was fitted up with wire. Raw force data were collected at 1000 Hz by analog-digital (AD) transducer (Eagle hab 3, Motion Analysis Corp., Santa Rosa, CA, USA). These data were simultaneously obtained with a 3-D motion capture system.

4.2.7.3 Kinematic and kinetic data

MATLAB (MathWorks inc., Massachusetts, USA) was used to conduct data processing and analysis. To reduce the error of numerical differentiation, the obtained positional data were smoothed using singular spectrum analysis (Alonso et al., 2005). MP joint angle (flexion/extension) was calculated using the positional data of markers attached to the index finger and the radial wrist. MP joint angular velocity was defined as the differential value of MP joint angle. From times series data of joint angular velocity and force, the time when joint angular velocity was almost constant except the beginning and the end of motion that is largely influenced by inertia was chosen as analysis period (Fig. 4-4).

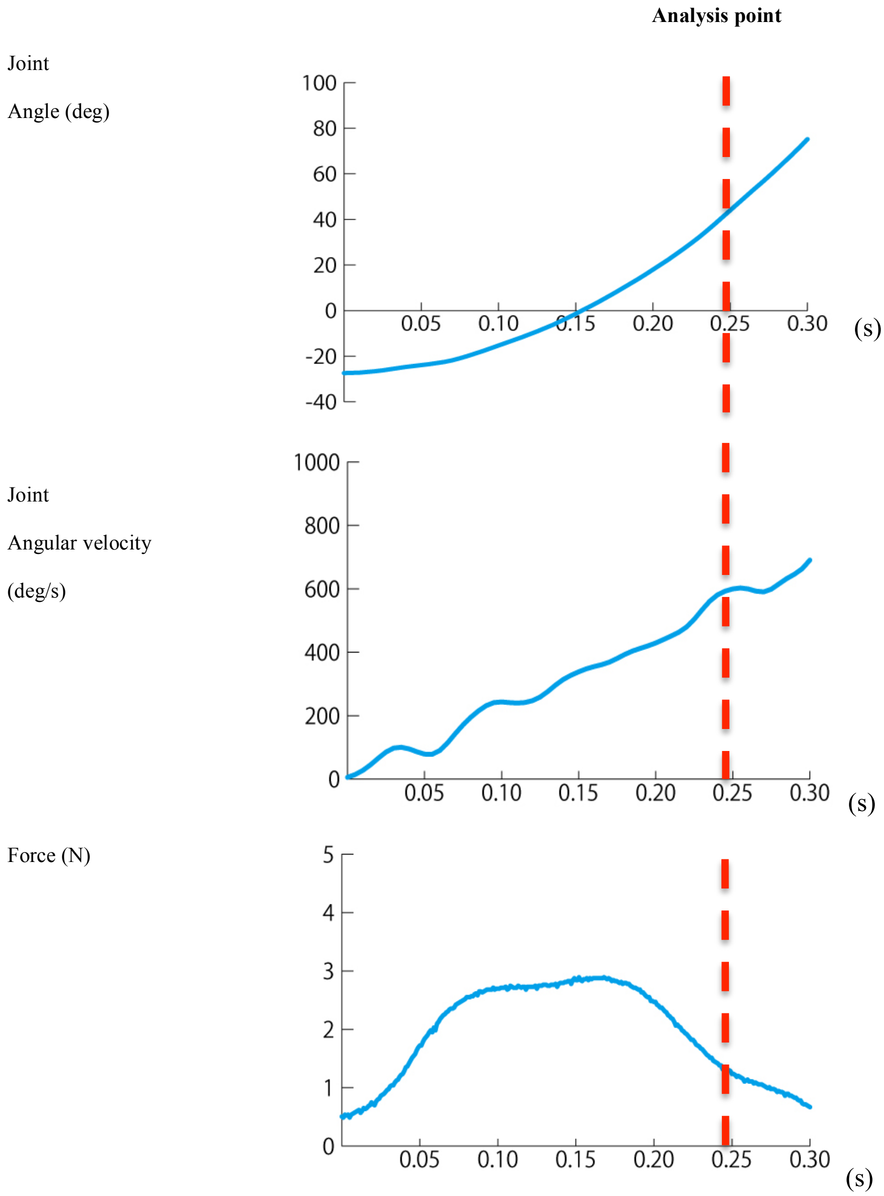


Fig. 4-4. A representative measurement of time series of joint angle, joint angular velocity and force at MP joint under 1.5 kg condition. 0 ms represents the beginning of fingers flexion.

The finger torque was calculated by multiplying the force by the moment arm length, that is the distance from the MP joint to fingertip of index finger. Obtained angular velocity was plotted in scatter diagram. Regression equation of concentric torque–angular velocity relationship was calculated from Hill characteristic equation.

$$(P + a)(V + b) = (P_0 + a)b \qquad (4\text{-}6)$$

where P is the torque, V is angular velocity, P_0 is the maximum isometric flexion torque, a and b is constant. From obtained regression equation, maximum shortening velocity (V_0: angular velocity when there is no load) was estimated by extrapolation. Other experimental observations (Abbott et al., 1952; Bigland-Ritchie and Woods, 1976) indicate that this equation is not applicable for eccentric force–velocity relationship. Mashima et al. (1972) propose a different hyperbolic relation. To ensure safety of the subject, the data during eccentric contraction was two points. Only trend line was indicated without using regression equation reported by Mashima et al. (1972).

4.2.9 Statistical Analysis

Tukey's multiple comparison tests determined the increase or decrease of the parameters joint torque and work. A probability of $p < 0.05$ indicated significance.

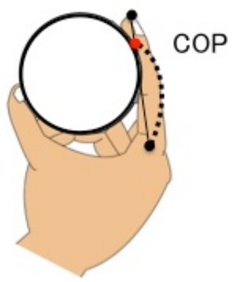
4-3. RESULTS

4.3.1 Ball Velocity

At first, it was examined whether subjects could throw balls with three different velocities. Tukey's post hoc multiple comparison tests indicated significant differences for all comparisons among slow (10.3 ± 1.4 (SD) m/s), medium (13.4 ± 1.7 m/s), and fast (16.0 ± 0.9 m/s) conditions ($p < 0.05$).

4.3.2 Kinematics of Wrist and Fingers

From -50 ms to ball release, the position of COP was closer to fingertip (83.0～85.8 % : relative to the distance from MP joint to fingertip) (Fig. 4-5).



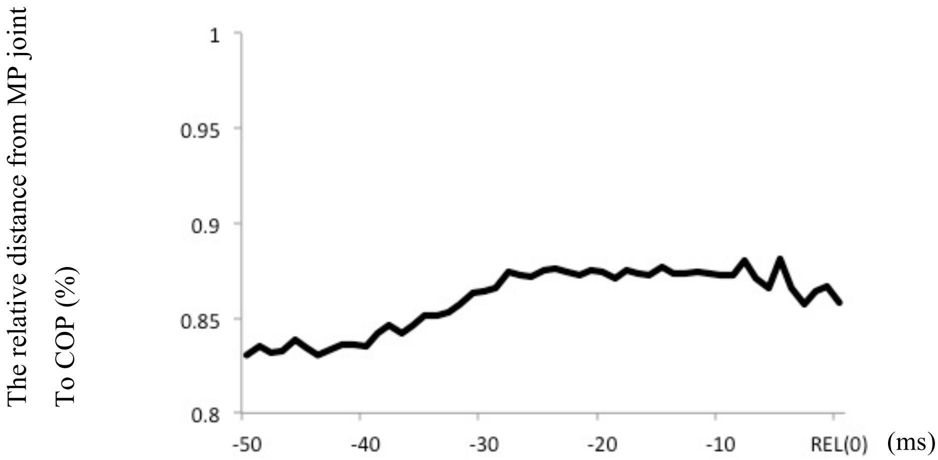


Fig. 4-5. The result of estimation of COP.

Regardless of ball velocity, finger extended until ball release, and begun to flex at the instant of final ball release (Fig. 4-6). Also, the wrist flexed from -50 ms to ball release irrespective of ball velocity.

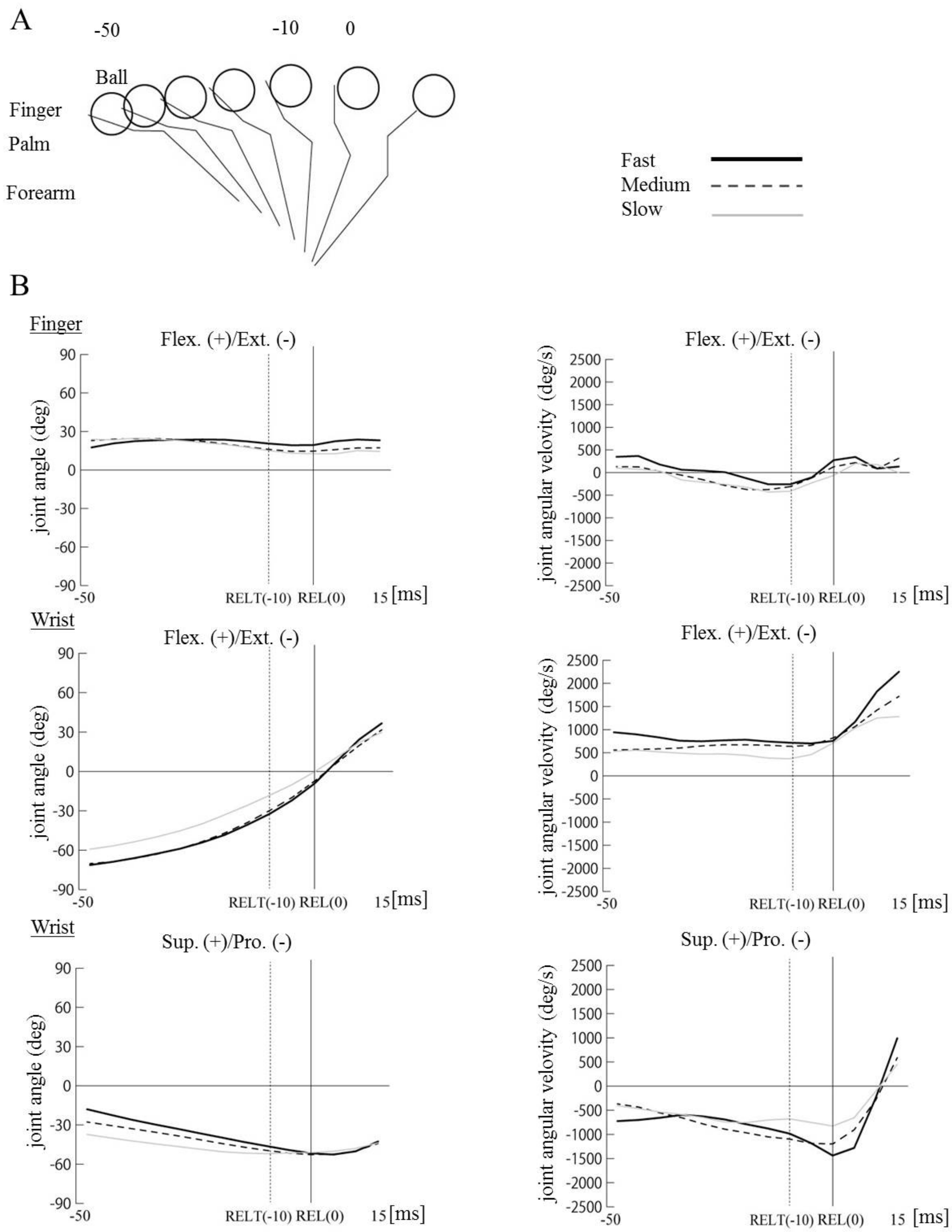


Fig. 4-6. Kinematic data (A: stick pictures B: joint angle and angular velocity) of finger and wrist joint for slow, medium, and fast conditions. Stick pictures show each segment and ball positions every 10 ms from 50 ms before ball release (REL) to 10 ms after REL. Ensemble averages (n = 6) of each joint angle and angular velocity for slow, medium, and fast condition.

4.3.3 Kinetics of Wrist and Fingers

Finger torque showed flexion torque until ball release (Fig. 4-7). Wrist torque showed flexion torque until ball release.

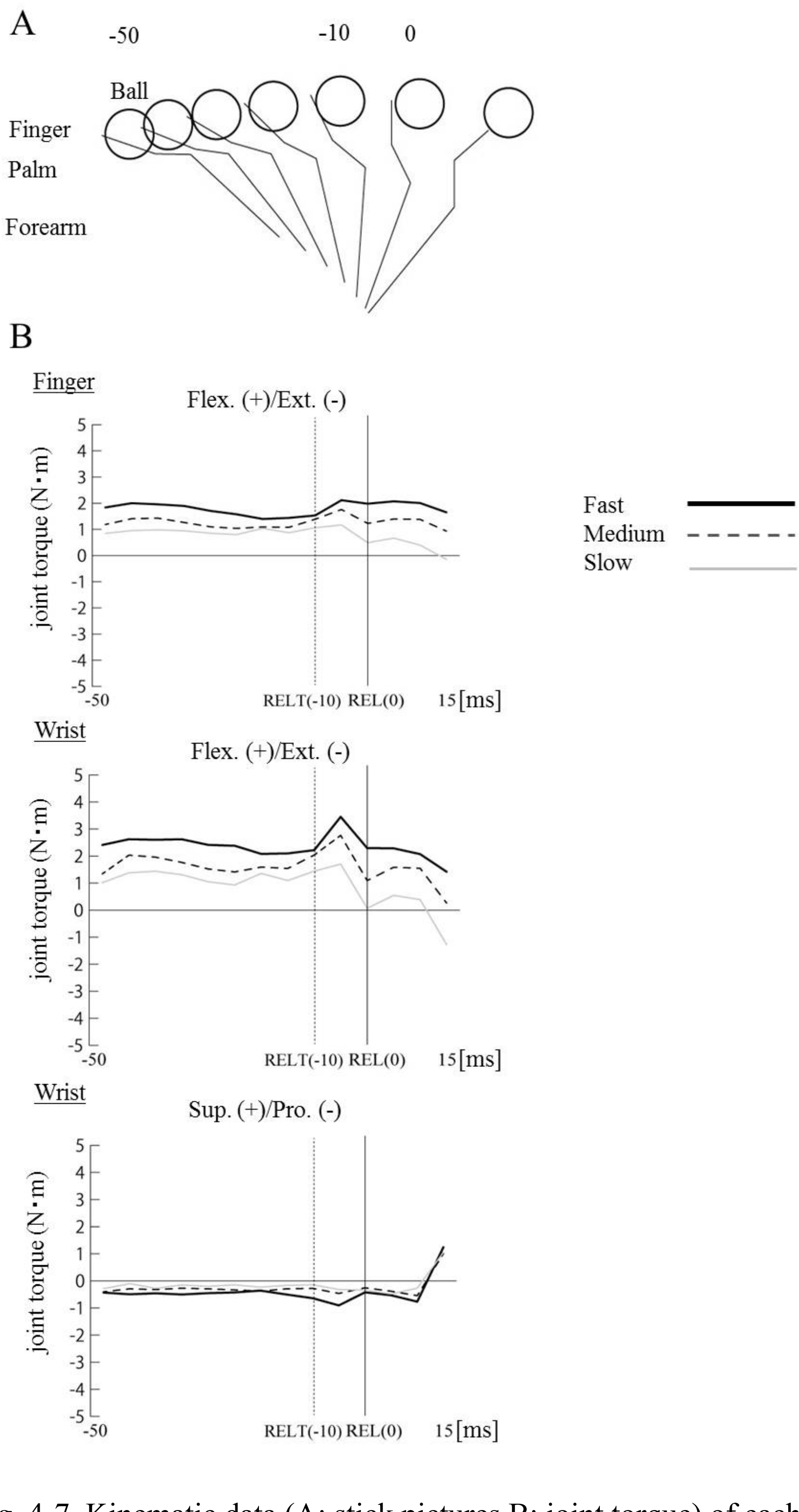


Fig. 4-7. Kinematic data (A: stick pictures B: joint torque) of each joint for slow, medium, and fast condition. Ensemble averages (n = 6) of each joint torque for slow, medium, and fast conditions.

The results of Tukey's multiple comparison tests in joint torque between ball velocities are shown in Fig. 4-8. This result indicates that skilled throwers increased the wrist and fingers torque with ball velocities.

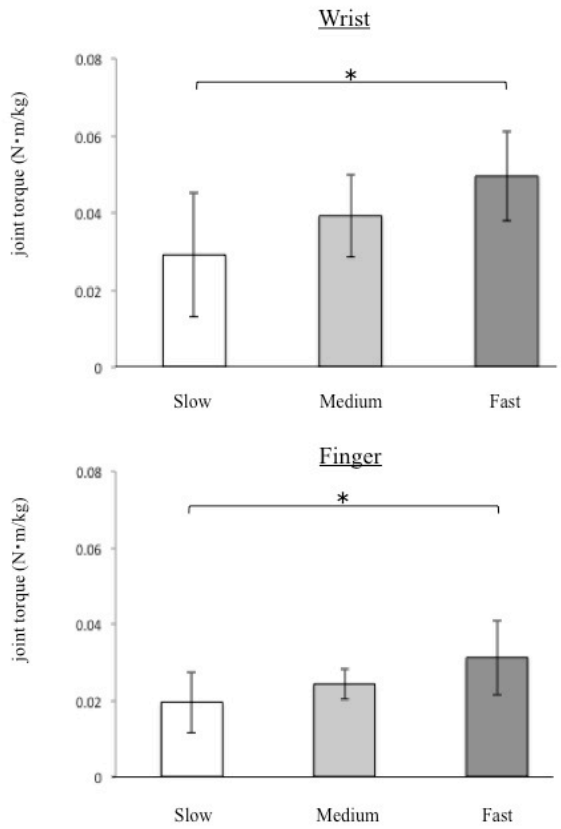


Fig. 4-8. Peak joint torque for each joint. *$P < 0.05$ (Tukey's multiple comparison test).

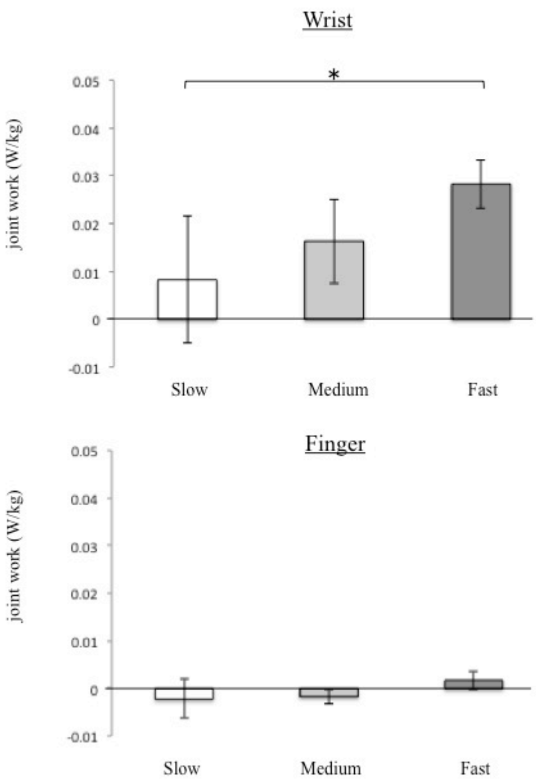


Fig. 4-9. Joint work from -50 ms to REL for each joint. *P < 0.05 (Tukey's multiple comparison test).

The results of Tukey's multiple comparison tests in work of wrist and fingers between ball velocities are shown in Fig. 4-9. This result indicates that skilled throwers increased the work of wrist with ball velocities. On the other hands, the work of fingers was kept relatively constant in spite of the increase of ball velocity.

4.3.4 Torque-Angle Relationship and Torque-Angular Velocity Relationship

The torque–angle relationship for fingers was the strength curve (the maximum torque versus joint angle) in which the strength measure first increases and then decreases as the joint angle increases (Fig. 4-10).

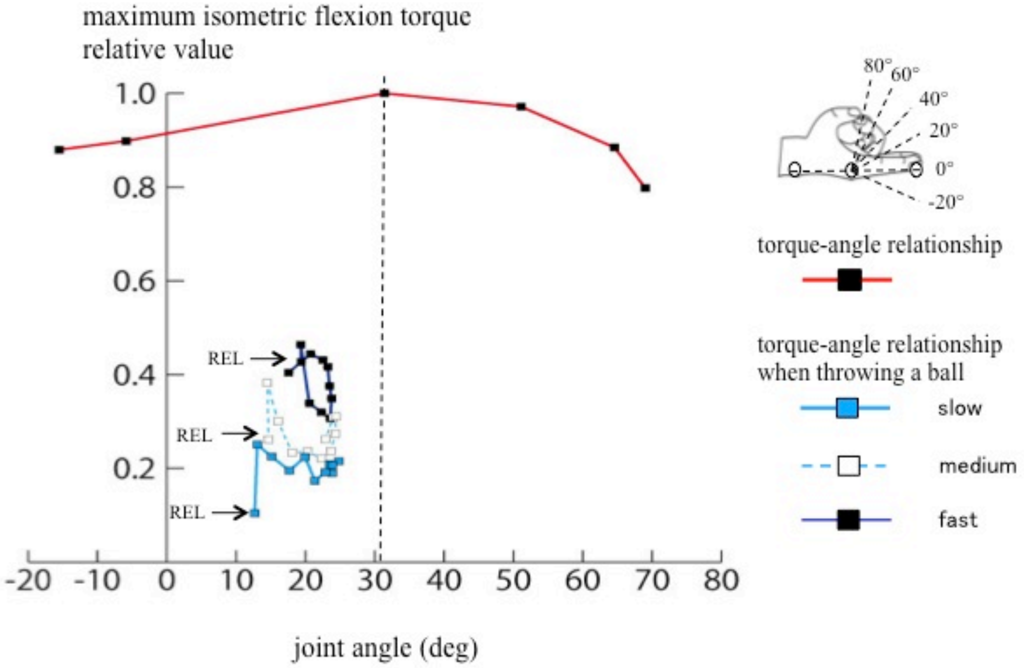


Fig. 4-10. Average torque-angle relationship observed when throwing a ball.

Average torque-angle relationship when throwing a ball superimposed on the torque-angle relationship for finger muscles.

The maximum isometric flexion torque was 4.3 N·m when the MP joint angle was 31°. Low strength values occurred during full fingers extension, where MP angle is small (e.g., -20 degrees), and at full fingers flexion, where MP angle is approximately equal to 70 degrees.

In the torque–angular velocity relationship, the concentric torque decreased with increasing velocity (Fig. 4-11).

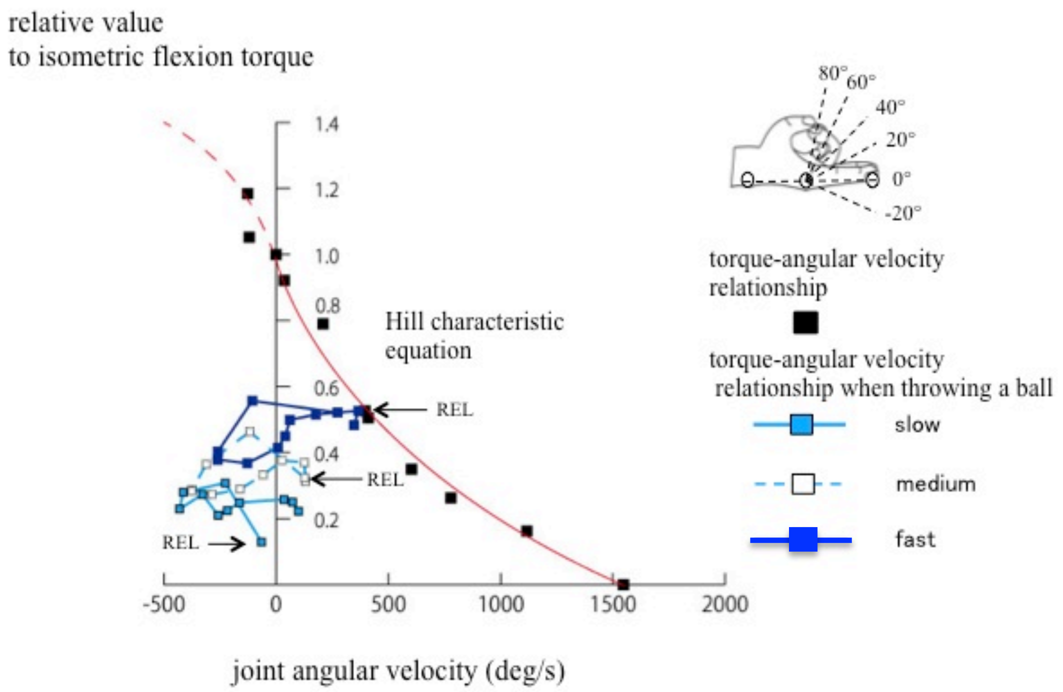


Fig. 4-11. Average torque-angular velocity relationship observed when throwing a ball.

Average torque-angular velocity relationship when throwing a ball superimposed on the torque-angular velocity relationship for finger muscles. The torque and angular velocity values were well fitted to the Hill characteristic equation.

On the other hand, the excentric torque increased with increasing velocity. The maximum isometric flexion torque (P_0) was 3.8 N·m, and the maximum velocity (V_0) was 1547 deg/s.

4.3.5 Finger Flexion Torque when Throwing a Ball Relative to the Maximal Voluntary Flexion Torque

The range of motion at fingers throughout the throw was small (slow: 9.7 ± 3.8 ~ 26.4 ± 8.5 degree, medium: 12.5 ± 3.6 ~ 30.2 ± 8.8 degree, fast: 12.3 ± 6.1 ~ 33.6 ± 4.4 degree) compared with wrist (slow: -59.2 ± 14.1 ~ 34.9 ± 13.9 degree, medium: -70.2 ± 9.7 ~ 39.0 ± 15.2 degree, fast: -71.3 ± 9.7 ~ 43.3 ± 16.2 degree). The finger flexion torque during ball throwing was exerted in the vicinity of the optimal joint angle in the torque–angle relationship and the maximum isometric torque in the torque–angular velocity relationship. In the torque–angle relationship for fingers, the value of flexion torque during ball throwing to maximum isometric flexion torque increased with ball velocities (slow: -6.7± 18.4 % to 26.6± 10.9 %, medium: 10.4± 8.3 % to 39.8± 15.6 %, fast: 18.5± 12.1 % to 51.5± 16.5 %). In the torque–angular velocity relationship, the value of flexion torque during ball throwing to maximum isometric flexion torque increased with ball velocities (slow: -7.5± 20.8 % to 30.1± 12.3 %, medium: 11.7± 9.4 % to 45.1± 17.6 %, fast: 21.0± 13.7 % to 58.3± 18.7 %).

4-4. DISCUSSION

4.4.1 The Adjustment of Ball Velocity by Wrist and Fingers

A first objective in this study was to examine the role of wrist and fingers under different ball velocity. From the results of Tukey's post hoc multiple comparison tests, it was indicated that subjects could throw the balls using three different velocities. Also, wrist torque and work increased with ball velocity. This indicates that wrist torque and work contributed to the adjustment of ball velocity.

Hirashima et al. (2007) reported that skilled ball throwers imposed the ball velocity adjustments on the wrist joint when the beneficial interaction torque was available in whole-body 3D throwing. This result supports the validity of our conclusion about the role of wrist during ball throwing.

Also, fingers torque increased with ball velocity. This result supported the hypothesis. However, the work of fingers was kept relatively constant in spite of the increase of ball velocity. This result suggests that it is unlikely that work of fingers directly contributed to the adjustment of ball velocity. Nevertheless, fingers torque increased with ball velocity. Thus, the role of fingers movement in ball throwing should not be neglected.

During rapid throwing motion, adjusting grip force according to ball acceleration to keep gripping the ball is necessary. If no joint torque was exerted, a ball would slip on the fingers before optimal release. Additionally, the range of motion at fingers throughout the throw was small compared with that at the wrist. This movement would lead to keeping the work of fingers relatively. Less movement at fingers throughout the throw contributes to producing stable base for accurate control of the fingers. From these results, it is considered that fingers flexion torque and joint work contributed to keep gripping the ball and achieve accurate ball release.

4.4.2 Torque-Angle Relationship and Torque-Angular Velocity Relationship

4.4.2.1 Torque-Angle Relationship

In the torque-angle relationship, the maximum isometric torque occurred when the fingers was in slight flexion. Based only on the present data it was not possible to draw conclusions concerning why this muscle-group specificity might occur. However, Kulig et al. (1984) reported that the change of maximum isometric torque to joint angle was due to length-force relationship in muscles, especially, due to length of moment arm. Thus, it was considered that the result in this study was determined by physiological factor. If MP joint flexes under wrist angle is kept constant, finger flexors (e.g. Flexor digitorum superficialis and flexor digitorum profundus) change their length. Thus, it was anticipated that the fingers' torque-angle relationship was influenced by finger flexors' length-force relationship. In addition, the pattern of torque-angle relationship at fast condition differs from slow and medium condition. This is due to difference of MP joint angle at -50 ms. In fast condition, fingers flexion angle at -50 ms was large (Fig. 4-6). It was anticipated that throwers flex fingers more and keep gripping the ball according to ball acceleration.

4.4.2.2 Torque-Angular Velocity Relationship

In the torque–angular velocity relationship, the concentric torque decreased with increasing velocity (Fig. 5B). This result was similar to the results for other joints reported in previous studies (e.g., Westing et al., 1988; Valour et al., 2003). On the other hand, it was indicated that eccentric torque tends to increase with increasing velocity. If additional increases in eccentric velocity occurs, it was considered that the maximum eccentric torque remained constant by neural inhibiting system (Westing et al., 1988). They explained that the system restrict the maximal tension in a muscle by an inhibitory feedback loop when very high levels of muscle tension might active. In this study, from perspective of safety, lengthening velocity was restricted. However, to confirm whether neural inhibiting system occurs when very high levels of fingers muscle tension might active, future studies will need to focus on fingers eccentric torque under high velocity.

4.4.3 Finger Flexion Torque when Throwing a Ball Relative to the Maximal Voluntary Flexion Torque

A second objective in this study was to evaluate the percentage of finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque. We could clarify that the percentage of finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque was -6.7± 18.4 % ～ 58.3± 18.7 %. Finger flexion torque during aimed throwing was performed in the vicinity of the optimal joint angle in the torque–angle relationship and the maximum isometric torque in the torque–angular velocity relationship. Larger finger flexion torques can be generated in those regions compared with those in other regions. Kurokawa et al. (2003) reported that the m. gastrocnemius medialis activated in the optimal region of the force-length relationship in human jumping. They suggested that this condition is advantageous for muscle fibers to generate relatively high force, which is required to accelerate the mass center of the body during the latter half of the push off phase. Similar phenomena have been reported during wallaby hopping (Biewener et al., 1998). In the case of ball throwing, expert baseball players can throw fastball (about 40 m/s) at more than twice as fast as the data in this study (fast condition: 16.0 ± 0.9 m/s). It was anticipated that force acting on the fingers from ball is very large when expert baseball players throws a ball at maximum effort. From these results, it was considered that fingers torque' activation in optimal region is advantageous for generating large flexion torque, which is required to counteract the reaction force from the ball.

4.4.4 Limitations

In this study, the measurement posture of wrist was in the neutral position. In ball throwing, the range of motion at wrist throughout the throw was relatively large. Ambike et al. (2013) reported that, in the static maximum voluntary contraction test, the highest grip strength occurred at wrist angles ranging from 0.5～50 degree in extension. Thus, torque–angle relationship for fingers would be influenced by measurement posture of wrist. For obtaining detailed knowledge about finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque, future studies will need to measure maximum fingers flexion torque at various wrist angle.

4-5. Summary of Chapter 4

This study had two objectives: (1) examining the biomechanical role of wrist and fingers under different ball velocity and (2) evaluating the percentage of finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque. From the results of Tukey's multiple comparison tests, it was indicated that wrist torque and work most contributed to the adjustment of ball velocity. Peak fingers torque increased with ball velocity. However, the work of fingers was kept relatively constant in spite of the increase of ball velocity. We anticipated that, fingers flexion torque and joint work contributed to keep gripping the ball and achieve accurate ball release.

Also, we could clarify that the percentage of finger flexion torque when throwing a ball relative to the maximal voluntary flexion torque was -6.7± 18.4 % ～ 58.3± 18.7 %. Finger flexion torque during aimed throwing was performed in the vicinity of the optimal joint angle in the torque–angle relationship and the maximum isometric torque in the torque–angular velocity relationship. From these results, it was considered that fingers torque' activation in optimal region is advantageous for generating large flexion torque, which is required to counteract the reaction force from ball.

CHAPTER 5

BIOMECHANICAL ROLE OF FINGERS DURING FASTBALL BALL AND CURVEBALL PITCHES

5-1. Introduction

In Chapter 2 and Chapter 3, to focus on general function of fingers during ball throwing, the first question of the study how fingers during ball throwing are controlled to accomplish both generation of ball velocity and accurate ball release was discussed. However, in these studies, there are some constraints (lack of full pitching motion, non-regulation ball with laces, short pitching distance, etc.) in order to obtain the data of fingers. Thus, restricted information is provided that is new or important for sport science which is largely interested in baseball. In Chapter 4, as a practical research, we focused on function of fingers during real baseball pitching.

In baseball, to get batter out, pitchers throw not only the fastball but also many different types of breaking ball. Specifically, curveball is one of the representative breaking balls. The primary focus of biomechanics researchers has been the evaluation of shoulder, elbow, and wrist joint kinematics and kinetics during fastball and curveball pitches (e.g. Sakurai et al., 1993; Barrentine et al., 1998) to determine the impact of pitching on these joints (Solomito et al., 2014). Sakurai et al. (1993) reported that there were no differences in the motions of the shoulder and elbow joints between fastball and curveball pitches. Also, Solomito et al. (2014) reported that the curveball was found to produce the greatest forearm supination and ulnar torque. These parameters were significantly different from the angle and torque noted when pitching fastball. In summary, the fastball and curveball pitches appear to have kinematic similarities at the shoulder and elbow but differences at the wrist and forearm data.

There is a published study describing the release pattern of fingers during fastball and curveball pitches (Stevenson, 1985). Also, Kinoshita et al. (2017) reported that the shear force peaks of index and middle fingers during fastball pitching occurred at 4-5 ms before ball release, and the peaks summed to 102 N. Matsuo et al. (2017) indicated that a mean force of 195$\pm$ 27 N during fastball pitching was applied in the proximal direction of the hand at the same time as the beginning of ball rolling. However, no study has described relationship between fingers torque and various pitches. Thus, kinetic analyses of fingers during several pitches have not been conducted, and the mechanism how fingers during baseball throwing are controlled to throw several pitch types is not understood well. Gaining a better understanding of the fingers motion will provide coaches and the researchers with a more complete description of the mechanics of the fingers and the differences created by different types of pitches. Thus, this study's first objective was to examine the mechanism how fingers torque are controlled to throw fastball and curveball.

In chapter 3, it was found that finger torque showed flexion torque until ball release regardless of ball velocity. Thus, we hypothesized that finger torque showed flexion torque until ball release in the fastball pitch. Elliott et al. (1986) considered that in curveball pitches the palm was turned so that fingers pressure was applied to the top outer quadrant of the ball to produce a combination of forward and sideward rotation of the ball. Probably, fingers will show adduction torque just before ball release in curveball pitch.

Alaways et al. (2001) reported that the trajectory of a pitched ball is determined by its initial linear and rotational velocities, the angle of release, the direction of the ball's axis of rotation, air density, and air viscosity. Among the parameters required to determime the pitched baseball trajectory, ball velocity has attracted the most attention from biomechanists (e.g. Matsuo et al., 2001; Stodden et al., 2005). However, the spin rate is also important in determining the pitched baseball trajectory. Several studies examined relationship between spin rate and ball trajectory (e.g. Higuchi et al., 2013; Mizota et al., 1997). Higuchi et al. (2013) reported that the decrease in accuracy of the batter's swing that was observed when the fastball's backspin deviated from the usual rate likely occurred because experienced batters predict ball trajectory from perceived ball velocity. Also, in breaking ball, the influence of spin rate on ball trajectory was examined. Mizota et al. (1997) reported that if spin rate of forkball is about 10 Hz, the ball sinks vertically near the home base. These results indicates that altering the spin rate is effective for getting batter out. Despite the importance of ball spin rate in baseball pitching, no study has reported how the spin rate of a pitched baseball is produced during the pitching motion. Thus, this study's second objective was to examine the factor that a pitcher exerts to produce the spin rate of a baseball. Whiteside et al. (2015) reported that the changeup rotated significantly slower than the fastball and curveball. They implies that the torque applied to the ball by fingers in the fastball and curveball would be significantly higher than that applied in the changeup. Thus, it is expected that the fingers torque is related to the ball spin rate.

5-2. Methods

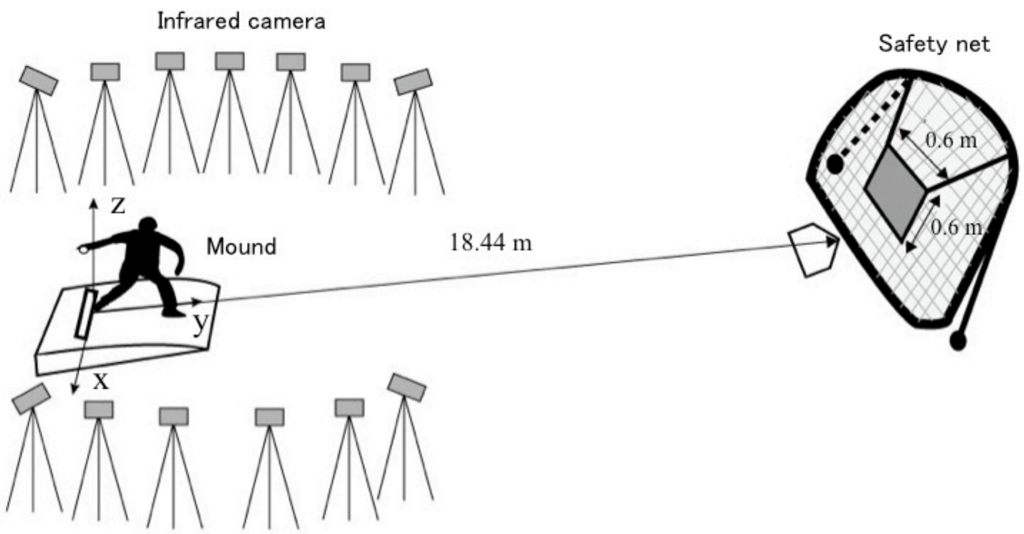
5.2.1 Experimental Design

Eight healthy male baseball pitchers (age: 19 ± 2 years, mass: 69 ± 7 kg, height:

1.71 ± 0.06 m) participated in the experiment with informed consent. Six pitchers played at high school, and two were collegiate pitchers (mean baseball experience: 11 ± 2 years). Five participants were right-handed, the others were left-handed. All the pitchers were regarded as either over-hand or three –quarter-hand pitchers.

All the experiments were conducted at National Institute of Fitness and Sports in Kanoya. After warming up using their normal routine, each pitcher performed pitching on an indoor pitching mound. All participants threw to a strike zone net located behind a home plate placed 18.44 m from the pitching rubber (Fig. 5-1A).

A



B

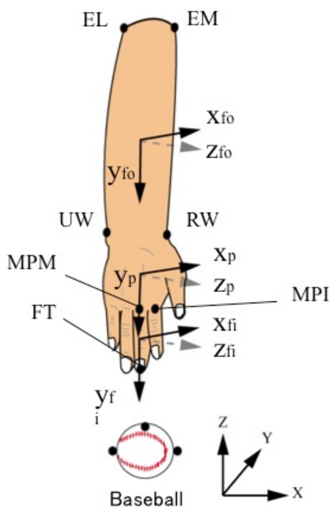


Fig. 5-1. The experimental setup (A: camera setting B: marker set).

We recorded three-dimensional arm movements by 3D-Motion Analysis System with thirteen cameras at 1000 Hz (Raptor Digital System, Motion Analysis Corp., Santa Rosa, CA, USA). Seven reflective markers were attached to the subject, and three markers were attached to the baseball. Field of view in this camera was 63°×52°.

The target was made of cloth, and its size was 0.6 m × 0.6 m. The target surroundings were covered with a safety net and mat. A rosin bag was prepared for those who wished to apply it on their fingers. The three trials were collected for two pitches (four-seam fastball and curveball). Each participant threw the four-seam fastball. The four-seam fastball is the most common pitch thrown in baseball games. Also, subjects were instructed to throw a curveball that throws with their feeling like 'pull the ball out'. Additional trials were collected as needed until three strikes had been thrown. When the ball did not hit the target, the trial was repeated. One trial for each pitcher was selected for analysis; this was the trial with the highest velocity pitch of the strike pitches.

5.2.2 Recording Movement

Eight reflective markers were attached to the subject's arm and three markers were attached to the baseball (Fig. 5-1B). The markers on the fingers and a ball were 14 mm in diameter, and the others (palm and forearm) were 19 mm in diameter. Motions were recorded at a sampling rate of 1000 Hz using a 3D motion analysis system (Raptor Digital System, Motion Analysis Corp., Santa Rosa, CA, USA). Field of view in this camera was 63°×52°.

5.2.3 Kinematic Data

The x-, y-, and z-axis in global coordinates were set to anterior–posterior, medial–lateral, and vertical directions, respectively (Fig. 2-3). The x-, y-, and z-axis in the local coordinate system were oriented to each segment. The x-, y-, and z-axis in the global and local coordinates system were same as Chapter 2 (see 2.2.4 for detail explanation of the kinematic data).

MATLAB (MathWorks inc., Massachusetts, USA) was used to conduct data processing and analysis. The instantaneous position of the ball center was estimated from the coordinates of the three reflective markers on the ball using the least-square technique, the position is equidistant from each marker. The instant of REL was defined as the instant at which the distance between the ball center and FT marker exceeded the sum of the radius of the ball (4.125 cm), radius of the FT marker (0.7 cm), and finger thickness (1.2 ± 0.1 cm; Jinji et al., 2011). The data from −50 ms to REL was kept for analysis. Stevenson (1985) reported that the thumb of the throwing hand comes off the ball at approximately 6 ms before ball release. Thus, data were analyzed relative to thumb contact (from -50 ms to -6 ms) and thumb release (-6ms to REL) phases. To reduce the error of numerical differentiation, the obtained positional data were smoothed using singular spectrum analysis (Alonso et al., 2005). Joint angles were calculated using the Cardan angle definition (x–y′–z″ sequence) (Winter, 2005). The rotation angle around the x-axis was defined as fingers flexion/extension and that around the z-axis as fingers adduction/abduction.

5.2.4 Kinetic Data

Using finger model (see 4.2.3 for detail explanation of the finger model), kinetics of fingers (torque, power and work) was calculated. The position of COP was calculated from force sensor data (see 4.2.4 for detail explanation of the estimation of COP). The power at each joint was calculated, and the work from −50 ms to REL was calculated by integrating the power with respect to time.

5.2.5 Ball Spin Rate and Spin Axis

The ball spin rate immediately after ball release was calculated from the three reflective markers attached to the pitched baseball using the methods described by Jinji and Sakurai (2006). Comparisons of kinematic and kinetic data were made between the high spin rate and low spin rate pitcher (difference in both data is more than 4 Hz) under similar ball velocity (difference in both data is less than 1.5 m/s) during each pitches. The spin axis was derived from the positional changes of the reflective markers attached to the baseball and the equation of a sphere. The center of the ball was defined as the origin of the local coordinate system of the ball, in which the x, y and z axes were parallel to the respective axes of the global reference frame and were assumed not to rotate (Fig. 5-2).

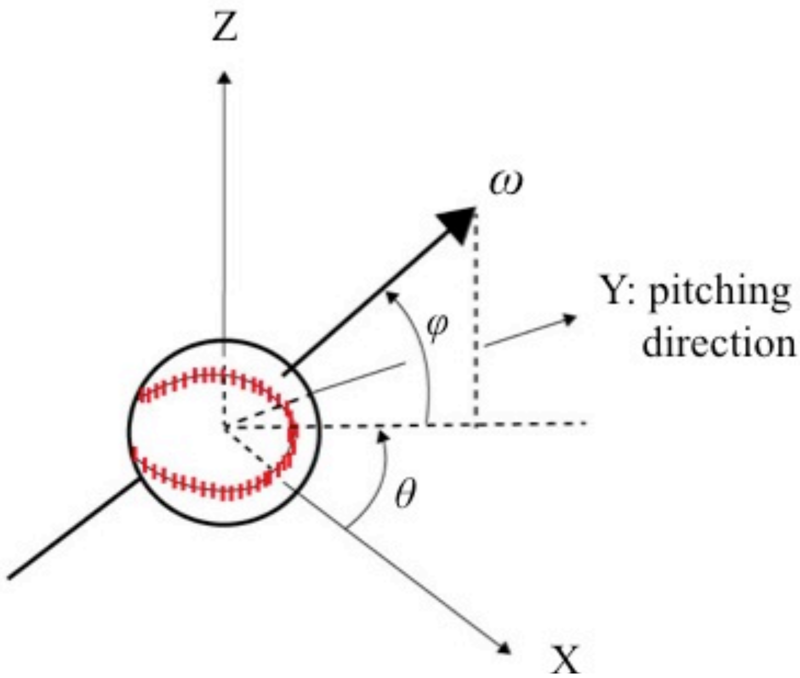


Fig. 5-2. Definition of the direction of ball spin axis with azimuth θ and elevation φ. When θ = 0 and φ = 0, the x, y, and z axes are parallel to the respective axes of the global reference frame.

The direction of the spin axis is defined by the elevation φ (the angle between spin axis and horizontal plane) and the azimuth θ (the angle between the x axis and the projection of the spin axis in the horizontal plane). The solutions were obtained for a total of three values, each of which was the combination of two out of three reflective markers. The angles of the spin axis and the spin rate were obtained as averages of the three values.

5.2.6 Cross-Correlation Analysis

To examine similarity between wrist joint torque and finger joint torque, a cross-correlation function was used. The data from −50 ms to 15 were kept for analysis. The data series of wrist joint torque (n = 8) was cross-correlated with the data series of finger joint torque (n=8). The maximal correlation coefficient and the time lag were calculated.

5.2.7 Statistical Analysis

Difference between four-seam fastball and curveball for the parameters (ball velocity, spin rate, spin axis, joint torque, and work) was analyzed using student's *t*-tests. A probability of $p < 0.05$ indicated significance.

5-3. RESULTS

5.3.1 Ball Velocity and Spin

Table 5-1 compared fastball, power-curveball, and curveball for ball velocity, spin rate, spin axis.

Table. 5-1. Differences in property of ball between pitch types.

	Fastball	Curveball	*p*–value
The Property of ball			
Ball velocity (m/s)	29.7±3.3	23.4±3.0	< 0.01
Spin rate(Hz)	26.1±5.0	22.7±5.4	–
Azimuth(°)	32.9±9.6	129.7±19.6	< 0.01
Elevation(°)	−22.6±9.7	32.7±11.7a	< 0.01

The listed values are in the form of ensemble average ($n = 8$) plus the SD. The average velocity of the fastball was 29.7 ± 3.3 m/s and was found to be significantly faster ($p < 0.01$) than the ball velocity of the curveball (23.4 ± 3.0 m/s). No significant differences of the mean spin rate was observed between pitch types. The mean value of the angles θ for fastball (32.9 ± 9.6 °) was significantly different from the curveball (129.7 ± 19.6 °) ($p < 0.01$). The mean value of the angles φ for fastball (-22.6 ± 9.7 °) was significantly different from curveball (32.7 ± 11.7 °) ($p < 0.01$).

5.3.2 Finger Kinematics

Fig. 5-3 shows stick pictures of one trial for a subject, when throwing balls at three pitches.

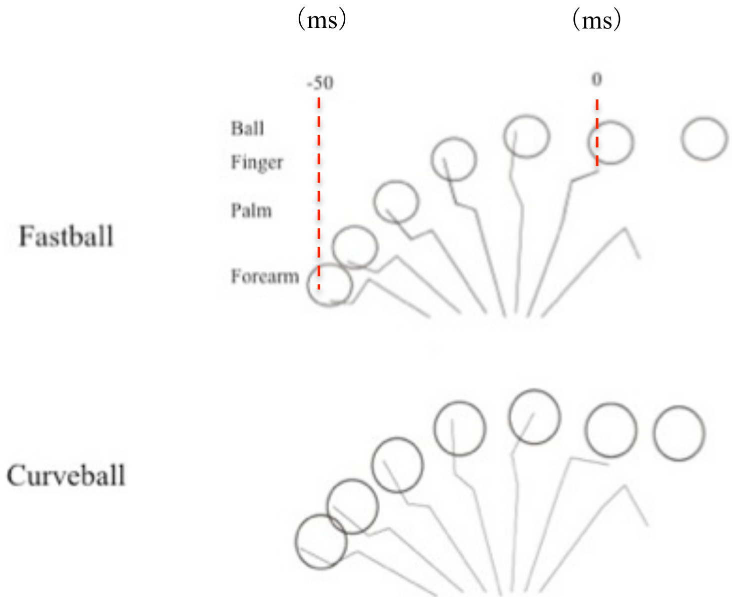


Fig. 5-3. Stick pictures at -50, -40, -30, -20, -10, 0, and 10 ms are drawn. Reconstruction of finger, arm and ball positions for a single throw shown. The finger is shown as 1 straight-line segment.

During thumb contact (from -50 ms to -6 ms) phase, the following motions occurred: fingers extension, fingers adduction (Fig. 5-4).

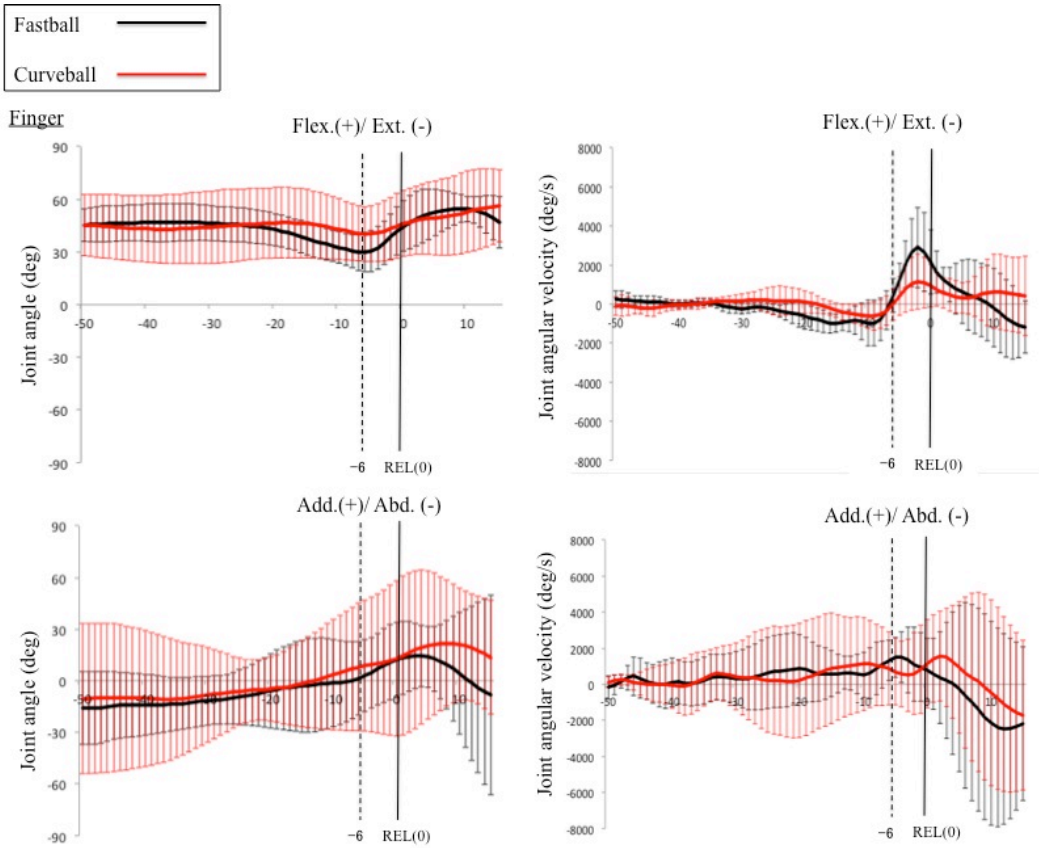


Fig. 5-4. Comparison of average and standard deviation of fingers' kinematic data. Ensemble averages (n=8) and standard deviation of MP joint angle and angular velocity. Thick black line is the fastball and red line is curveball. The solid vertical line is REL, and the dotted vertical line is -6 ms.

For fastball pitch, rapid fingers extension occurred at about -6 ms. During thumb release (from -6 ms to REL) phase, the following motions occurred: fingers flexion, fingers adduction. There were no statistically significant differences of the peak finger flexion angle between pitch types (Table 5-2).

Table. 5-2. Differences in fingers kinematics and kinetics between pitch types.

	Fastball	Curveball	*p*-value
Joint angle			
Peak fingers flexion angle (°)	50.2±11.6	53.1±19.3	–
Peak fingers adduction angle (°)	17.3±21.0	43.7±5.4	< 0.01
Peak fingers abduction angle (°)	−29.1±12.9	−41.3±16.5	< 0.01
Joint angular velocity			
Peak fingers flexion angular velocity (deg/s)	3169.9±1862.2	1491.4±1292.2	< 0.01
Peak fingers extension angular velocity (deg/s)	−1531.0±646.6	−977.6±413.6	< 0.05
Peak fingers adduction angular velocity (deg/s)	2913.4±1124.3	2827.0±1309.0	–
Peak fingers abduction angular velocity (deg/s)	−1442.8±1097.8	−1917.7±2064.8	–
Joint torque			
Peak fingers flexion/extension torque (N･m)	14.7±4.6	14.6±7.2	–
Peak fingers adduction/abduction torque (N･m)	0.1±1.4	4.5±2.9	< 0.05
Work			
Fingers flexion･extension (J/kg)	0.010±0.037	−0.003±0.024	–
Fingers adduction･abduction (J/kg)	−0.007±0.009	0.038±0.042	< 0.05

Peak finger adduction angle for curveball was significantly larger than fastball (fastball: 17.2 ± 21.0 °, curveball: 43.7 ± 8.5 °). Also, peak finger abduction angle for curveball was significantly larger than fastball (fastball: -29.1 ± 12.9 °, curveball: -41.3 ± 16.5 °). Peak finger flexion angular velocity for fastball was significantly larger than curveball (fastball: 3169.9 ± 1862.2 deg/s, curveball: 1491.4 ± 1292.2 deg/s). Peak finger extension angular velocity for fastball was significantly smaller than curveball (fastball: -1531.0 ± 646.6 deg/s, curveball: -977.6 ± 413.6 deg/s). No significant differences of the peak finger adduction/abduction angular velocity was observed between pitch types.

5.3.3 Finger Kinetics

During thumb contact phase, the following joint torque occurred: fingers flexion torque, fingers abduction torque (Fig. 5-5).

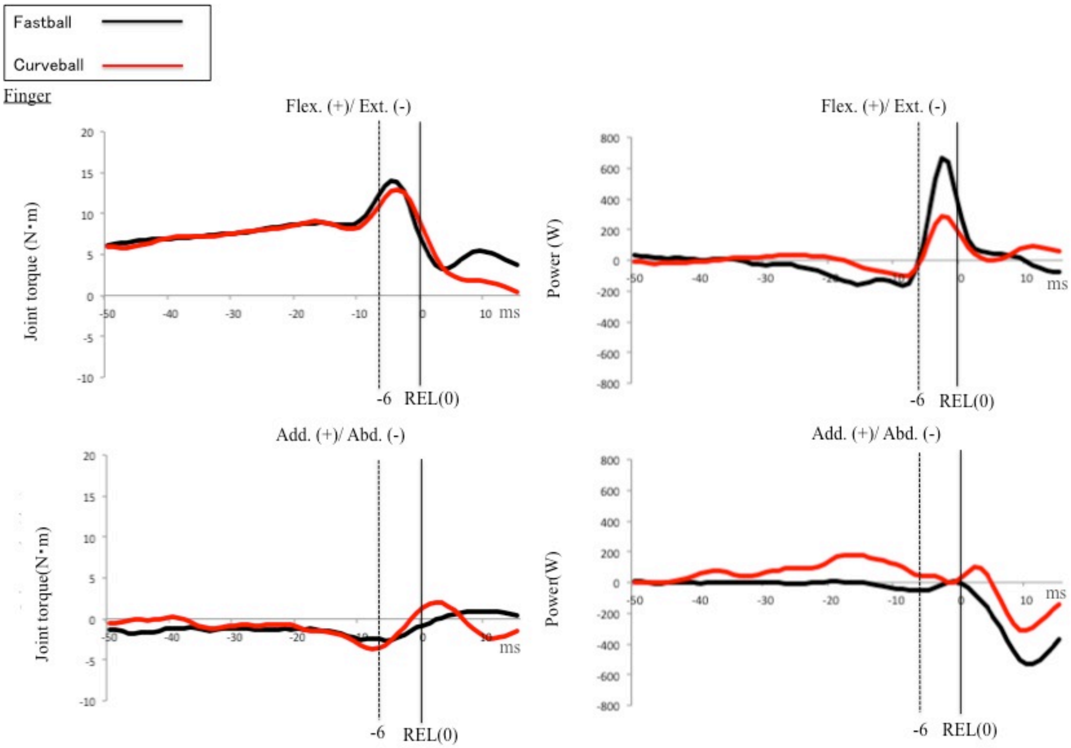


Fig. 5-5. Comparison of mean fingers' kinetic data. Ensemble averages (n=8) of fingers joint torque and power.

Similarly, during thumb release phase, the following joint torque occurred: fingers flexion torque, fingers abduction torque. No significant differences of the peak finger flexion/extension torque was observed between pitch types. Peak finger adduction/abduction torque for curveball was significantly larger than fastball (fastball: 0.2 ± 1.3 N·m, curveball: 3.7 ± 1.2 N·m). No significant differences of finger flexion/extension work was observed between pitch types. Finger adduction/abduction work for curveball was significantly larger than fastball (fastball: -0.007 ± 0.009 J/kg, curveball: 0.008 ± 0.042 N·m). At wrist joint, flexion torque always occurred (Fig. 5-6). In cross-correlation analysis of the finger model, the maximal correlation coefficient between wrist flexion torque and finger flexion torque during fastball pitch was very high (r = 0.94 ± 0.05). The time lag at maximal correlation coefficient was zero (t = 0 ± 0 ms). Compared with fastball pitch, the maximal correlation coefficient between wrist flexion torque and finger flexion torque during curveball pitch was low (r = 0.44 ± 0.84). The time lag at maximal correlation coefficient was zero (t = 1.5 ± 2.3 ms).

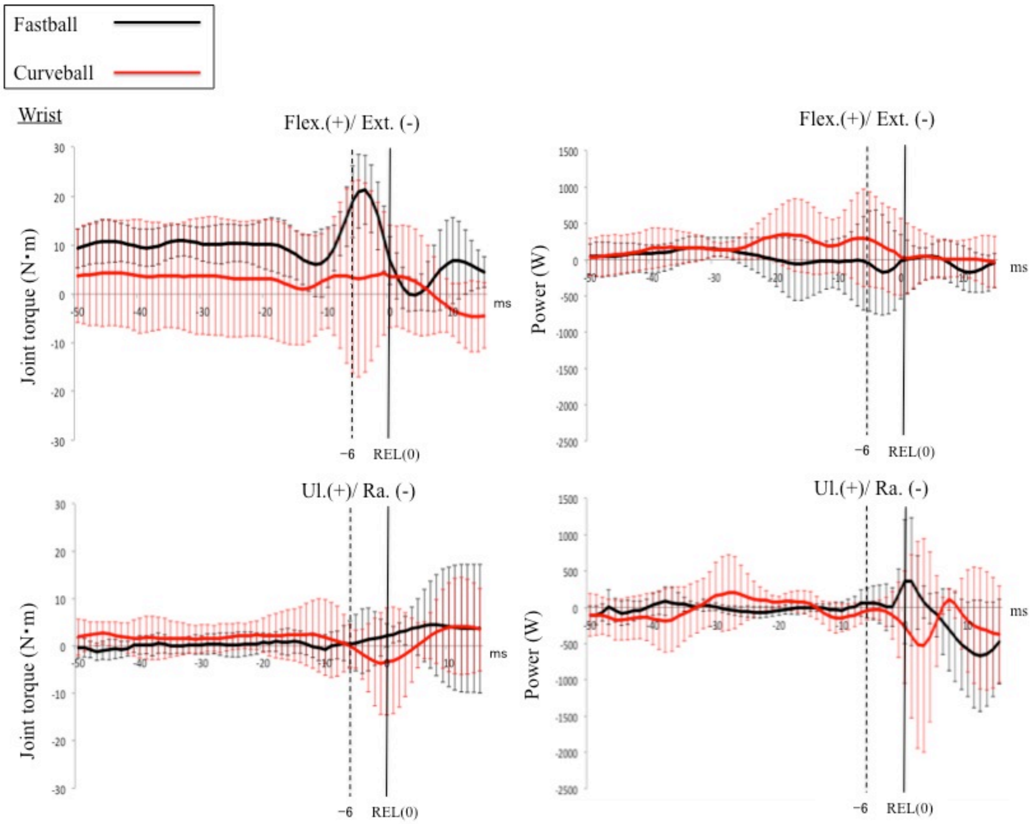


Fig. 5-6. Comparison of average and standard deviation of wrist' kinematic data. Ensemble averages (n=8) and standard deviation of wrist joint angle and angular velocity. Thick black line is the fastball and red line is curveball. The solid vertical line is REL, and the dotted vertical line is -6 ms. Ul., ulnar deviation; Ra., radial deviation

5.3.4 Comparison of Kinematic and Kinetic Data Between High and Low Spin Rate Pitcher under Similar Ball Velocity

During fastball pitches, fingers flexion angle at ball release was smaller in high spin pitcher (subject A, ball velocity: 34.2 m/s, spin rate: 33.3 Hz) compared to the low spin pitcher (subject B, ball velocity: 34.6 m/s spin rate: 27.3 Hz) (high spin pitcher: 41.3 °, low spin pitcher: 68.8 °) (Fig. 5-6).

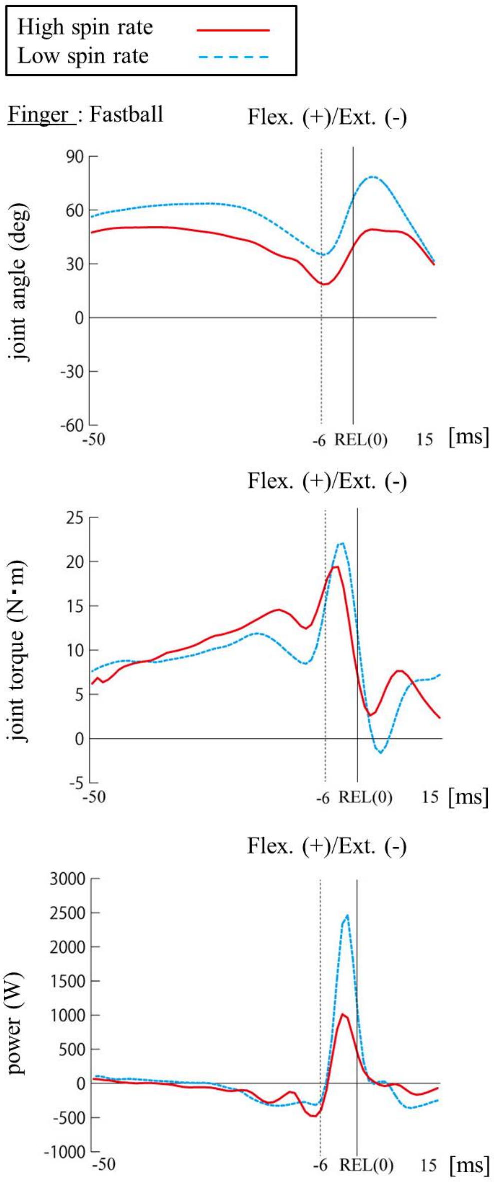


Fig. 5-6. Comparison of kinematic and kinetic data between high (subject A, ball velocity: 34.2 m/s, spin rate: 33.3 Hz) and low spin rate (subject C, ball velocity: 34.6 m/s spin rate: 27.3 Hz) pitcher under similar ball velocity during fastball pitches. Thick red line is the high spin rate, dashed cyan line is low spin rate.

Additionally, compared to the low spin rate pitcher, the high spin rate pitcher indicated less peak fingers flexion torque (high spin pitcher: 19.4 N · m, low spin pitcher: 22.0

N · m) and power (high spin pitcher: 1013.3 W, low spin pitcher: 2460.7 W) before ball release. In kinetic parameter, the others with similar velocity showed the same trend (Table. 5-3); peak fingers torque and power in high spin rate pitchers was smaller than that of low spin rate pitchers.

In contrast, during curveball pitches, fingers flexion angle at ball release was larger in high spin pitcher (subject B, ball velocity: 24.8 m/s, spin rate: 27.5 Hz) compared to the low spin pitcher (subject H, ball velocity: 24.8 m/s, spin rate: 19.5 Hz) (high spin pitcher: 78.4 °, low spin pitcher: 50.0 °) (Fig. 5-7).

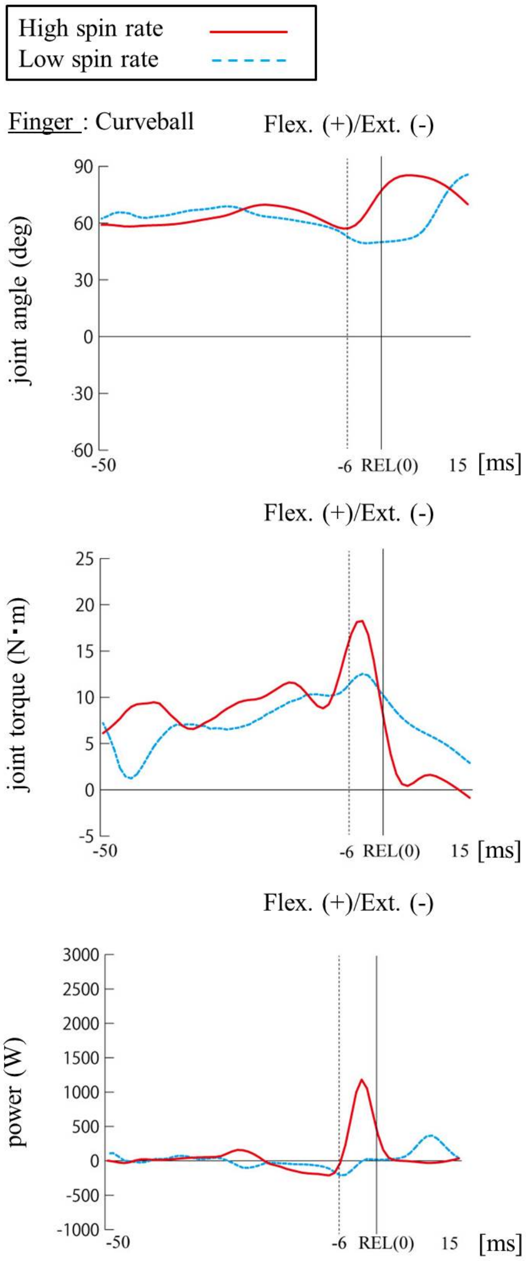


Fig. 5-7. Comparison of kinematic and kinetic data between high (subject C, ball velocity: 24.8 m/s, spin rate: 27.5 Hz) and low spin rate (subject B, ball velocity: 24.8 m/s, spin rate: 19.5 Hz) pitcher under similar ball velocity during curveball pitches.

Additionally, compared to the low spin rate pitcher, the high spin rate pitcher indicated larger peak fingers flexion torque (high spin pitcher: 18.2 N · m, low spin pitcher: 12.5

N · m) and power (high spin pitcher: 1180.6 W, low spin pitcher: 113.1 W) before ball release. In fingers flexion torque, the others with similar ball velocity showed the same trend (Table. 5-3); peak fingers torque in high spin rate pitcher was larger than that of low spin rate pitcher.

Fastball	Group1		Group2		Group3	
Parameter	High spin rate 33.3 Hz 34.2 m/s Subject A	Low spin rate 27.3.Hz 34.6 m/s Subject C	High spin rate 29.9 Hz 27.1 m/s Subject B	Low spin rate 26.0 Hz 26.8 m/s Subject F	High spin rate 25.1 Hz 29.2 m/s Subject D	Low spin rate 20.5 Hz 29.3 m/s Subject E
Peak fingers flexion angle (°)	50.4	68.8	53.1	31.3	54.9	37.1
Peak fingers joint torque (N·m)	19.4	22	9.2	11.7	12.4	15.8
Peak fingers power (W)	1013.3	2460.7	170.9	358.8	395.9	449.7

Curveball	Group4		Grup5	
Parameter	High spin rate 27.5 Hz 24.8 m/s Subject C	Low spin rate 19.5.Hz 24.8 m/s Subject B	High spin rate 23.7 Hz 20.7 m/s Subject F	Low spin rate 19.6 Hz 19.9 m/s Subject H
Peak fingers flexion angle (°)	78.4	68.8	31.3	56.4
Peak fingers joint torque (N · m)	18.2	12.5	11.7	10.0
Peak fingers power (W)	1180.6	113.2	43.8	59.6

Table. 5-3. Comparison of kinematic and kinetic parameter between high and low spin rate pitchers under similar ball velocity during fastball and curveball pitches. Peak fingers power indicated the peak of the positive power.

5-4. DISCUSSION

5.4.1 Validation of Kinematic Data

The mean fastball velocity and spin rate in this study (velocity: 29.7 ± 3.3 m/s, spin rate: 26.1 ± 5.0 Hz) was lower than previous study that high school and collegiate-aged baseball pitchers participated (velocity: 34.0 ± 3.1 m/s, spin rate: 27.4 ± 3.5 Hz) (Jinji et al., 2011). This may be due to differences in skill level. In previous study, some professional pitchers participated. Additionally, the competition level of collegiate sample was top level in Japan. The spin rate did not differ between the fastball and breaking ball. This result is similar to previous study's result (e.g. Jinji & Sakurai, 2006; Whiteside et al., 2015). Also, the values of spin axis of fastball in this study (θ : 32.9 ± 9.6 °, φ : -22.6 ± 9.7 °) matched previous studies [θ : 34.9 ± 14.1 °, φ : -28.4 ± 9.8 ° (Jinji et al., 2011)]. In addition, with respect to curveball, the values of spin axis (curveball θ : 129.7 ± 19.6 °, φ : 32.7 ± 11.7 °) indicated similar trend [θ : 112.6 ± 21.5 °, φ : 21.9 ± 8.6 ° (Whiteside et al., 2015)]. Overall, the similarities between the results of this study and previous studies support the validity of kinematic data.

5.4.2 Characteristic of Fastball and Curveball

When curveball was compared with the fastball, it could distinguish clearly. The average velocity of the curveball was found to be significantly slower than the ball velocity of the fastball. The spin rate did not differ between the fastball and curveball pitches. Additionally, both the elevation and azimuth angles were significantly larger in the curveball compared with the fastball. From these results, curveball was defined as follows. Curveball has a lower ball velocity, similar spin rate, and different direction of the spin axis.

5.4.3 Control of Fingers during Fastball and Curveball

This study's first objective was to examine the mechanism how fingers torque is controlled to throw fastball and curveball. Peak finger flexion angular velocity for fastball was significantly larger than curveball. Matsuo et al. (2017) reported that PIP and DIP joint at fingers during fastball pitching indicated very high flexion angular velocity just before ball release. This result supports the validity of kinematic data in our study. Also, peak fingers adduction/abduction angle, torque, and work for fastball was lower than curveball. From these results, it was considered that it is necessary motion for fastball pitching to flex fingers just before ball release rapidly.

Peak finger adduction/abduction torque for curveball was significantly larger than fastball. Additionally, in the curveball pitch, fingers torque quickly reversed its direction from abduction to adduction just before ball release. This result is consistent with the hypothesis that fingers would show adduction torque in curveball pitch. Finger adduction/abduction work for curveball was significantly larger than fastball. These motions appear to coincide with the common coaching methods that describe the motion as pulling the first two fingers down over the side of the ball to throw a good curveball (Jordan, 1988). Solomito et al. (2014) reported that the curveball was found to produce the greatest wrist ulnar torque. These parameters were significantly different from the torque noted when pitching fastball. These results suggest that wrist ulnar deviation and fingers adduction just before ball release rapidly are necessary motion for curveball pitching.

In this study, complete synchronization of wrist torque and fingers torque during fastball pitch was found (no significant delay of peak finger flexion torque). This result is similar to the result of Chapter 3. It suggests, even if high-speed fastball throwing, the CNS seems to have synchronized wrist torque and fingers' torque by feed-forward adjustments to stabilize release timing. On the other hand, the maximal correlation coefficient between wrist joint torque and finger joint torque during curveball pitch was low ($r = 0.44 \pm 0.84$; Fig. 5-8), and the standard deviation was large.

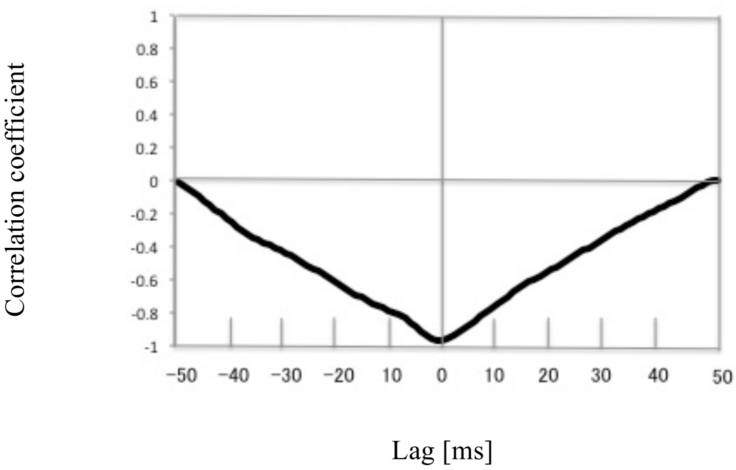


Fig. 5-8. A representative result (subject D) of the cross correlation function between wrist joint torque and finger joint torque during curveball pitch.

This result is due to two pitchers data (subject A and D). The maximal correlation coefficient except subject A and D was high ($r = 0.89 \pm 0.09$). The maximal correlation coefficient in subject A and D were, respectively, -0.90 and -0.93. This result indicates that two throwers exerted anti-phase movement of wrist torque and fingers torque during curveball pitch. Stevenson (1985) reported that approximately 75 % of the curveball pitches were thrown in a thumb-middle-index sequence and approximately 25 % of the curveballs had a middle-thumb-index release sequence. Probably, these results could be indicative of different styles of coaching experienced by the pitchers involved in this study when learning these pitching mechanics. On the other hand, the common point of these two types is that fingers produced flexion torque. Thus, it was considered that fingers flexion torque is essential to grip the ball and produce topspin specific to curveball.

5.4.4 The Factor Producing the Spin Rate of a Pitched Baseball

This study's second objective was to examine the factor that a pitcher exerts to produce the spin of a ball. It was examined relationship between finger motion and ball spins in individual subjects with similar ball velocities. Especially, we focused on fastball and curveball that not only spin axis but also ball velocity was a significantly different from fastball.

In fastball pitch, peak fingers flexion torque and its power in high spin rate pitchers (the difference of spin rate between two pitches was more than 3.0 Hz) was smaller than that of low spin rate pitchers with similar ball velocities. This result suggests that fingers flexion torque and power is less effective for producing ball spin rate during fastball pitching. It was expected that fingers flexion torque before ball release would contribute to accelerating the ball because fingers flexion torque rotates the fingers in the ball's direction of travel. Probably, force acting parallel to the surface of the ball (shear force) would be the factor for generating backspin on the ball. Kinoshita et al. (2017) reported that the shear force peaks of index and middle fingers occurred at 4-5 ms before ball release, and the peaks summed to 102 N. However, in finger model, the term of shear force acting on the ball is not included in the equations. Thus, future study will need to measure shear force and ball spin rate during baseball pitching simultaneously.

On the other hand, low spin rate in fastball is not bad for pitchers. If the backspin rate of fastball is relatively lower than that of fastball with similar ball velocity thrown by the mean pitchers, the upward lift force of the pitched baseball become small, and the ball would drop. As a result, the batters' predictions would be wrong, and they would often miss the ball. Thus, if pitcher want to acquire the fastball that has a low spin rate, it is important that the coaches often say that the index and middle fingers push (flexion movement) behind the ball just before ball release.

Contrast to fastball, in curveball pitch, peak fingers flexion torque in high spin rate pitchers was larger than that of low spin rate pitchers with similar ball velocities. Also, peak fingers flexion torque for curveball was higher than peak adduction torque for curveball. These results suggest that fingers flexion movement is effective for producing ball spin rate during curveball pitching. Stevenson (1985) reported that 72.7 % of CB pitch was thrown in a thumb-middle-index finger release sequence, and the thumb comes off the ball at approximately 6.4 ms before ball release. Probably, the ball moves from thumb to middle finger and starts topspin. This time is just before that when peak fingers flexion torque occurred (-9.0 $\pm$ 13.4 ms). Pushing the ball (flexion torque) just before ball release would move the ball upward and generate topspin. From these results, it is considered that producing large fingers flexion torque just before ball release leads to imparting greater topspin to the ball.

5.4.5 Limitations

The large standard deviations were presented in the results of this study, which indicates that there is a great deal of inter-pitcher variability. Especially, work at fingers varied from pitcher to pitcher. Solomito et al. (2014) suggested that large standard variations of pitcher's motion could be indicative of different styles of coaching experienced by the pitchers involved in this study when learning how to use fingers during fastball and breaking ball pitching. In fact, it was reported that there were three types of fingers release patterns for curveball pitching (Stevenson, 1985). Other factors affecting inter-pitcher variation in work at fingers may include friction between ball and fingers. In this study, many pitchers who wished to apply it on their fingers used a powdered rosin. The use of powdered rosin would influence contact time between ball and fingers and shear force (Kinoshita et al., 2017). Also, the optimum level of moisture of the finger pad for achieving maximum friction as well as the finger pad area can differ from one person to another (Adams et al., 2013). For obtaining detailed knowledge about the relationship between ball and fingers in overarm throwing, future studies will need to examine friction between ball and fingers focusing on an individual pitcher.

5-5. Summary of Chapter 5

This study had two objectives: (1) examining the mechanism how fingers torque is controlled to throw fastball and curveball and (2) examine the factor that a pitcher exerts to produce the spin rate of a baseball. Peak finger flexion angular velocity for fastball was significantly larger than curveball. The fastball seems to be caused by the motion of rapid fingers flexion just before ball release. Peak finger adduction/abduction torque for curveball was significantly larger than fastball. Additionally, in the curveball pitch, fingers torque quickly reversed its direction from abduction to adduction just before ball release. Also, finger adduction/abduction work for curveball was significantly larger than fastball. These results suggest that curveball were caused by the motion of rapid fingers adduction just before ball release. In fastball pitch, peak fingers flexion torque and its power in high spin rate pitchers was smaller than that of low spin rate pitchers with similar ball velocities. This result suggests that fingers flexion movement is less effective for producing ball spin rate during fastball pitching. Contrast to fastball, in curveball pitch, peak fingers flexion torque in high spin rate pitchers was larger than that of low spin rate pitchers with similar ball velocities. It is considered that producing large fingers flexion torque just before ball release leads to imparting greater topspin to the ball.

CHAPTER 6

GENERAL DISCUSSION

Baseball throwing requires complex control and coordination of many body segments. In baseball pitching, the coaches often emphasize that it is important that the pitcher throws a fastball and breaking ball as the same throwing motion as possible not to be judged a pitch before ball release by the batter. That is, it is ideal that the motion of all segments except fingers is unified among pitches. To grip the ball and release it during baseball pitching, a pitcher must supply an adequate fingers torque. Thus, it is considered that control of fingers torque is a significant factor for baseball pitching. In this thesis, the mechanisms how fingers torque is controlled to accomplish baseball pitching were investigated. Various biomechanical analyses of ball throwing were conducted in this thesis, and the fingers coordination and the control strategies of ball throwing in humans were revealed. Through this thesis, a link segment model considering fingers during ball throwing (Chapter 2) was developed, the mechanism of fingers' torque control to accomplish both generation of ball velocity and accurate ball release (Chapter 3 and Chapter 4) was investigated, and the mechanism of fingers' torque control to throw several pitch types (Chapter 5) was investigated.

6-1. Finger Model and Conventional Model during Ball Throwing

Using a link segment model considering fingers (finger model), two findings were revealed: (1) MP joint torque can be obtained and (2) wrist flexion/extension torque can be calculated more accurate than the conventional model (Chapter 2). It was revealed that the reliability of MP joint torque in the fingers model was 83 %. This error is not a inherent problem in this method, but merely a problem of measurement precision. By improving only measurement precision of ball acceleration, the reliability can be 99 % at the maximum. It was concluded that application of finger model for analyzing ball throwing was valid.

6-2. Fingers' Torque Control Strategies in Ball Throwing

Integrating the findings of Chapter 3, 4 and 5, it was found that wrist torque and work contributed to the adjustment of ball velocity, and fingers torque and joint work contributed to keep gripping the ball and achieve accurate ball release. Previous studies reported that sequential muscle activity was observed from the scapular protractors to the shoulder horizontal flexors and from the shoulder horizontal flexors to the elbow extensor. However, wrist torque and fingers torque were activated at almost the same peak time (Chapter 3,5). Also, wrist torque and work increased with ball velocity (Chapter 4). On the other hand, the work of fingers was kept relatively constant in spite of the increase of ball velocity, though fingers torque increased with ball velocity. This result suggests that it is unlikely that work of fingers directly contributed to the adjustment of ball velocity.

Dounskaia et al. (1998) suggetsted a hierarchical control, in which the role of the proximal muscle is to generate movement of the whole linkage and the role of distal muscle is to produce corrections of the movement necessary to fulfill the task. Thus, it was anticipated that skilled throwers effectively utilized shoulder, elbow, and wrist torque and produced larger their angular velocity to satisfy the demand of rapid throwing movement. On the other hand, the role of fingers torque is to stabilize release timing to fulfill accurate throw rather than to accelerate the ball by itself. The high angular velocities at the shoulder, elbow, and wrist joints generate centrifugal and Coriolis forces (Hirashima & Ohtsuki, 2008; Stodden et al., 2005). In addition, in ball throwing, strong inertial forces act on the fingertips for thrusting the ball at high linear velocity (Kinoshita et al., 2017). To prevent the ball slipping out of the hand by these forces, a thrower must supply an adequate amount of fingers torque. Also, release timing's precise control is the most important factor for accurate throwing. In fact, a 1-ms delay in fingers' extension causes a 2.2-degree change in the ball's direction. Thus, to stabilize release timing, the throwers seems to have synchronized wrist torque and fingers' torque by feed-forward adjustments. In summary, to accomplish both generation of ball velocity and accurate ball release during ball throwing, skilled throwers imposed the ball velocity adjustments on the wrist joint, and gripping the ball and accurate ball release on the fingers joint.

6-3. Strategies for Generating Different Ball Spin by Skilled Throwers

In baseball pitching, the coaches often emphasize that it is important that the pitcher throws a fastball and breaking ball as the same throwing motion as possible not to be judged a pitch before ball release by the batter. That is, it is ideal that the difference of motion of all segments except fingers is minimized among pitches. Previous comparisons of kinematic data for shoulder and elbow revealed similarities between fastball and curveball pitches. Also, several studies reported that the forearm was supinated more in the curveball compared to the fastball, whereas the wrist was extension more in the fastball compared to the curveball (e.g. Sakurai et al., 1993; Barrentine et al., 1998). In this study, peak finger adduction/abduction torque for curveball was significantly larger than fastball. Also, finger adduction/abduction work for curveball was significantly larger than fastball. These results suggest that forearm, wrist and fingers contribute to pitching selectively as much as possible as with the same motion. Additionally, during fastball and curveball pitch, there was an apparent difference in fingers torque and power between high spin rate pitchers and low spin rate pitchers. Thus, it was considered that fingers torque and power control the spin rate of ball during baseball pitching.

6-4. Conclusion

The fingers' torque during baseball throwing was investigated by various biomechanical analyses, and the fingers coordination and the control strategies of ball throwing were discussed in this thesis.

We developed a link segment model considering fingers (finger model). Using finger model, two findings were revealed: (1) MP joint torque can be obtained and (2) wrist flexion/extension torque can be calculated more accurate than the conventional model.

During ball throwing, wrist torque and fingers torque were activated at almost the same peak time. Also, wrist torque and work increased with ball velocity. On the other hand, the work of fingers was kept relatively constant in spite of the increase of ball velocity, though fingers torque increased with ball velocity. From these results, to accomplish both generation of ball velocity and accurate ball release during ball throwing, skilled throwers would impose the ball velocity adjustments on the wrist joint, and gripping the ball and accurate ball release on the fingers joint.

Peak finger adduction/abduction torque and work for curveball was significantly larger than fastball. Previous comparisons of kinematic data for shoulder and elbow revealed similarities between fastball and curveball pitches. Additionally, during fastball and curveball pitch, there was an apparent difference in fingers torque and power between high spin rate pitchers and low spin rate pitchers. Thus, it was considered that fingers torque during baseball pitching contributes to producing different ball spin properties (the direction of ball spin, spin rate, spin axis) as much possible as the same whole body motion. In summary, from our studies, the biomechanical role of fingers torque during baseball throwing was revealed: (1) fingers torque stabilizes release timing synchronizing with wrist torque and (2) fingers torque contributes to producing different ball spin properties (the direction of ball spin, spin rate, spin axis) as much possible as the same whole body motion.

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