

博士（人間科学）学位論文

Intersegmental Dynamics and
Optimality in Rapid Aiming Movements

急速な狙準運動の最適化とその力学的特性

2005年1月

早稲田大学大学院 人間科学研究科

Masashi Yoshida
吉田 雅司

研究指導教員： 鈴木 秀次 教授

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF HUMAN SCIENCES AT WASEDA UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN HUMAN SCIENCES

INTERSEGMENTAL DYNAMICS AND
OPTIMALITY IN RAPID AIMING MOVEMENTS

By

MASASHI YOSHIDA

January 2005

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to many people for their contribution in the preparation of this dissertation. My deepest gratitude goes to Dr. Shuji Suzuki for his insightful guidance and continuous encouragement throughout my doctoral work.

Without his academic expertise and assistance, this dissertation would not have been possible. Extreme thanks are also expressed to other committee members, Drs.

Yoshiaki Nakajima, Hiroshi Fujimoto, and Yasuo Kawakami. They were a source of much wisdom and support. Their thoughtful comments and suggestions definitely helped in elaboration of this dissertation. Special gratitude is expressed to Dr. Jim Cauraugh, a former supervisor, as well as Drs. Chris Janelle and John Chow for their guidance and assistance during my master's work at the University of Florida, U.S.A. My appreciation extends to each member of Suzuki Laboratory at Waseda University, Japan, for his/her favorable support. I am especially grateful to Koh Inoue for his generous assistance in data collection. Finally, extra special thanks are extended to my family for their generous support and understanding.

TABLE OF CONTENTS

ACKNOWLEDGMENTS		iii
ABSTRACT		ix
CHAPTERS		
I	INTRODUCTION	1
	Statement of the Problem	2
	Statement of the Purpose	3
	Research Hypotheses	4
	Overview	5
II	REVIEW OF LITERATURE	6
	Woodworth's Legacy	6
	Two-component model of limb control	6
	Time to process visual feedback in controlling movement	8
	Models of Speed-Accuracy Relations in Goal-Directed Movements	10
	Fitts' law	10
	Iterative correction model	11
	Single-correction model	13
	Impulse variability model	14
	Optimized submovement model	17
	Control of Goal-Directed Movements: Kinematic Evidence	20
	Inherent errors in primary submovements	20
	Feedback-based corrective processes	21
	Optimality in Goal-Directed Movements	25
	Changes in the role of vision with practice	25
	Changes in control strategies with practice	28
	Summary	30
III	INTERSEGMENTAL DYNAMICS	32
	Fundamentals	33
	Kinematic coupling	33
	Motion-dependent effects	35

Applications	38
Empirical findings in motor control	38
Implications for rapid aiming movements	39
IV EXPERIMENT 1: INHERENT ERRORS	41
Method	42
Participants	42
Task, apparatus, and procedure	42
Data reduction: Intersegmental dynamics	44
Data analyses: Dependent measures	45
Results and Discussion	46
Limb kinematics and dynamics	46
Performance outcomes	51
V EXPERIMENT 2: CONTROL STRATEGIES	54
Method	55
Participants	55
Task, apparatus, and procedure	56
Data reduction: Intersegmental dynamics	57
Data analyses: Dependent measures	57
Results and Discussion	58
Performance outcomes	58
Limb kinematics and dynamics	60
VI EXPERIMENT 3: INSTANT ADAPTATION	67
Method	68
Participants, task, and apparatus	68
Procedure	68
Data reduction and analyses	68
Results and Discussion	69
Performance outcomes	69
Limb kinematics and dynamics	70
VII GENERAL DISCUSSION	76
Inherent Errors	76
Control Strategies	77
Instant Adaptation	78
Limitation and Future Direction	80
Conclusions	81

APPENDICES

A	INTERSEGMENTAL DYNAMICS -----	82
B	MOMENT OF INERTIA -----	84
C	INFORMED CONSENT -----	85
	RELATED ARTICLES -----	88
	REFERENCES -----	89
	BIOGRAPHICAL SKETCH -----	97

LIST OF FIGURES

Figures

3.1	Kinematics and Dynamics of a hand-held stylus movement to a target involving motions at the shoulder, elbow, and wrist joints -----	34
3.2	An exemplar time series of net joint moment and its components at the elbow during rapid aiming movement -----	37
4.1	The experimental setup -----	43
4.2	An exemplar time series of limb kinematics and dynamics at the shoulder during rapid aiming movements for a representative participant, plotted as a function of test conditions and temporal constrains -----	47
4.3	An exemplar time series of limb kinematics and dynamics at the elbow during rapid aiming movements for a representative participant, plotted as a function of test conditions and temporal constrains -----	49
4.4	Mean performance outcome measures and standard errors as a function of test conditions and temporal constrains -----	52
5.1	Mean performance outcome measures and standard errors as a function of trial block and vision -----	59
5.2	An exemplar time series of limb kinematics and dynamics at the shoulder during rapid aiming movements for a representative full-vision and no-vision participants, plotted as a function of trial block -----	61
5.3	An exemplar time series of limb kinematics and dynamics at the elbow during rapid aiming movements for a representative full-vision and no-vision participants, plotted as a function of trial block -----	62
5.4	Mean average limb dynamics in the acceleration and deceleration phases at the shoulder as a function of trial block and vision -----	63
5.5	Mean average limb dynamics in the acceleration and deceleration phases at the elbow as a function of trial block and vision -----	64
6.1	Mean performance outcome measures and standard errors as a function of test condition and vision -----	69

6.2	An exemplar time series of limb kinematics and dynamics at the shoulder during rapid aiming movements for a representative full-vision and no-vision participants, plotted as a function of test condition -----	71
6.3	An exemplar time series of limb kinematics and dynamics at the elbow during rapid aiming movements for a representative full-vision and no-vision participants, plotted as a function of test condition -----	72
6.4	Mean average limb dynamics in the acceleration and deceleration phases at the shoulder as a function of test condition and vision -----	73
6.5	Mean average limb dynamics in the acceleration and deceleration phases at the elbow as a function of test condition and vision -----	74

ABSTRACT

This study was designed to provide further evidence on how goal-directed movements were controlled and what were the mechanisms responsible for the relationship between movement speed and accuracy. In particular, three experiments were conducted dealing with the intersegmental dynamics of rapid aiming movements. The results of Experiment 1 clearly demonstrated that errors were inherent in the primary submovements that increased as a function of the level of active muscle force output. Experiment 2, however, indicated that depending on the abilities to use on-line visual feedback, different control strategies were possible to ensure optimal performance. More importantly, Experiment 3 showed that participants instantly adapted their control strategies to avoid a deteriorating loss in performance. Such instant adaptation of control strategies was interpreted as the flexibility of the human motor control system to compensate during rapid aiming movements through a reciprocal interplay between central planning and on-line feedback processing.

CHAPTER I INTRODUCTION

The control of limb movements is essential for everyday life. Day and night, humans are required to reach for a target in space, to pick up an object, and to make other wide varieties of goal-directed movements. Many of those movements are performed so effortlessly yet are necessary to compromise with an inherent nature of human motor behavior, a *speed-accuracy trade-off*. Faster movements can usually occur only at the expense of being spatially less accurate on the average, and spatially more accurate movements can usually occur only at the expense of being slower on the average (e.g., Fitts, 1954; Woodworth, 1899). This study extends our current knowledge of how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy.

A great deal of research over the past century has clearly demonstrated that movements toward a target consist of two components, an initial impulse (or primary submovement) followed by current control (or corrective submovement) (e.g., Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Woodworth, 1899). In essence, visual feedback reduces spatial errors to a greater extent. Temporal constraints of the movements, however, restrict time to process visual feedback (e.g., Keele & Posner, 1968), and thus the accuracy advantage by vision gradually decreases as a function of the movement speed. In the meantime, the magnitude of the initial impulse has a lawful relation to the dispersion of the primary movement endpoints that defines the extent to which feedback-based corrective processes must operate (e.g., Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979).

More recently, there has been much attention to the relative contributions of central planning and on-line feedback processing in controlling goal-directed movements (e.g., Elliott, Chua, Pollock, & Lyons, 1995; Khan, Elliott, Coull, Chua, & Lyons, 2002; Khan & Franks, 2000, 2003). Typically, a performer with vision tends to increase the velocity of the primary submovement to bring the limb to the vicinity of the target quickly. Although faster movements lead to greater variability in movement endpoints, this strategy allows the performer more time available for visual feedback utilization in the corrective submovements. As a consequence, the performer becomes increasingly proficient at central planning and controlling highly practiced movements as the construction of sensorimotor representations within the central nervous system (Ivens & Marteniuk, 1997; Proteau, Marteniuk, Girouard, & Dugas, 1987). By contrast, a performer without vision generally produces a slower but less variable primary submovement to abandon visually-guided error corrections. The findings suggest optimality in goal-directed movements through a reciprocal interplay between central planning and on-line feedback processing.

Statement of the Problem

Despite a considerable amount of research on the mechanisms underlying goal-directed movements, only limited attempts have been made to quantify the mechanical causes of movements. In multi-joint aiming task, neural-processing transforms visuospatial information about the initial hand position and the target location into motor commands to specify muscle forces and joint motions that move the hand to the desired location (Desmurget, Pelisson, Rossetti, & Prablanc, 1998). This perceptual-motor transformation needs to take into consideration the dynamic properties of the moving arm. Limbs are systems of linked bodies, and thus the

motion of a particular segment affects other segments in a kinetic chain, even if a given segment is not exposed to active muscle forces. Studies merely manipulating kinematic parameters, however, cannot account for these motion-dependent effects. A method of the intersegmental dynamics is, by contraries, useful to estimate the active and passive contributions to the movement trajectories.

Statement of the Purpose

This study dealt with the intersegmental dynamics of rapid aiming movements to provide further evidence on the mechanisms underlying goal-directed movements. Of particular interest was how humans adapted their control strategies in ensuring optimal performance. For this purpose, three experiments were conducted.

In Experiment 1, spatial accuracy of rapid aiming movements was examined by differentiating limb dynamics while keeping limb kinematics constant. Numerous studies have demonstrated that variable errors in participants' movement endpoint increase as a function of movement speed (e.g., Fitts, 1954; Kim, Carlton, Liu, & Newell, 1999; Meyer et al., 1988; Schmidt et al., 1979; Woodworth, 1899). Based on the assumption that faster movements are associated with greater forces, the level of force output is generally treated as a primary determinant of such variability (e.g., Meyer et al., 1988; Schmidt et al., 1979). In multi-joint movements, however, the completely different limb dynamics but the same limb kinematics would be possible. Some caution is therefore warranted before one examines the mechanical causes of movements.

Experiments 2 and 3 focused on how changes in movement outcomes and kinematics were reflected in movement dynamics. In literature, the accommodations to the motion-dependent effects were evident (e.g., Gribble & Ostry, 1999; Heise &

Cornwell, 1997; Hirashima, Kudo, & Ohtsuki, 2003; Hoy & Zernicke, 1986; Schneider, Zernicke, Schmidt, & Hart, 1989). Nevertheless, how visual feedback is used in controlling the intersegmental dynamics and the ways that this input may change as a function of practice are still not fully understood. In the context, Experiment 2 examined the effects of practice and vision, and Experiment 3 examined the effect of withdrawing vision on the intersegmental dynamics of rapid aiming movements.

On the basis of the findings from Experiments 1, 2 and 3, optimality in rapid aiming movements was discussed. This general discussion was comprehensively made in detail regarding *inherent errors*, *control strategies*, and *instant adaptation*.

Research Hypotheses

In Experiment 1, spatial errors in rapid aiming movements would increase with the average velocity of the movements. Furthermore, a lawful relation between errors and active contributions to the movement trajectories was expected if the level of force output was a primary determinant of the movement variability (e.g., Meyer et al., 1988; Schmidt et al., 1979).

Experiment 2 expected the accommodations to the motion-dependent effects with practice (e.g., Heise & Cornwell, 1997; Schneider et al., 1989). On the other hand, vision might have only a slight impact on these accommodations (e.g., Gordon, Ghilardi, & Ghez, 1995; Sainburg, Ghez, & Kalakanis, 1999; Sainburg, Ghilardi, Poizner, & Ghez, 1995). Nevertheless, different control strategies would emerge through the intersegmental dynamics depending on the abilities to use on-line visual feedback (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003).

In Experiment 3, to avoid a deteriorating loss in aiming accuracy due to the withdrawal of vision (e.g., Proteau, 1992; Proteau, et al., 1987), participants would adapt their control strategies by instantly altering the intersegmental dynamics.

Rational behind this hypothesis was optimality in goal-directed movements through a reciprocal interplay between central planning and on-line feedback processing (e.g., Khan et al., 2002; Khan & Franks, 2000).

Overview

Following Chapter 1 as an introduction, Chapter 2 provides comprehensive account of numerous details in goal-directed movements through an existing extensive body of research. Then, Chapter 3 discusses the fundamentals and applications of the intersegmental dynamics. Next three chapters, Chapter 4, 5 and 6 concerns Experiments 1, 2 and 3, respectively. Finally, Chapter 7 presents a general discussion about the findings from Experiments 1, 2 and 3.

CHAPTER II REVIEW OF LITERATURE

Many physical skills involve sequences of actions in which a selected part of the body must be shifted quickly and accurately from one place to another in space. Such goal-directed movements are often necessary for individuals to compromise between temporal and spatial characteristics of the movements. For more than a century, considerable amount of research has been devoted to studying how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy. The present chapter provides comprehensive account of numerous details in goal-directed movements through an existing extensive body of research.

Woodworth's Legacy

Two-component model of limb control

Often cited, the interest in how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy dates back over 100 years to the work of Woodworth (1899). In his doctoral dissertation, published as a seminal monograph by *Psychological Review*, Woodworth systematically examined “the accuracy of voluntary movement.” His experiment involved an aiming procedure in which participants made horizontal sliding movements back and forth (i.e., reciprocally) with a pencil over the surface of paper secured to a drum rotating at a constant speed. Drawing lines on the paper

allowed Woodworth to measure the spatial accuracy and consistency of the movement endpoints as well as the spatiotemporal characteristics of the movement trajectories.

Woodworth's (1899) findings are still relevant today. In most aiming attempts, the initial portion of the movement was relatively rapid and stereotyped. However, as the pencil approached the target (or target distance), the movement became slower and was characterized by discontinuities in the time-displacement profile. He suggested that movements toward a target consist of two components, an initial impulse followed by current control. The initial impulse is hypothesized to be under central control and designed to bring the limb into the vicinity of the target. Once in the region of the target, the limb comes under current or feedback control. In current control, visual information about the relative position of the limb and the target is used to make any necessary adjustments of the movement trajectory to home the limb in on the target. This model has come to be known as the *two-component model* and been an important foundation underling the derivation of some of the most influential theories on limb control and speed-accuracy trade-offs (see Elliott, Helsen, & Chua, 2001 for a review).

Woodworth (1899) consequently focused on feedback processing in current control to examine the relation between speed and accuracy in goal-directed movements. Participants performed their horizontal sliding movement to beats of a metronome set at the rate of 20 to 200 movements per min (expected duration being 3.0 to 0.3 s per movement) under two different vision conditions. In one condition, participants had their eyes open; thus visual feedback was available throughout each moment. In the other condition, their eyes were closed; thus no visual feedback was available. As metronome speed increased (i.e., as movement time decreased), spatial errors of the eyes-open condition approached those of the eyes-closed condition. The

idea was that the temporal constraints of the movement restricted an opportunity for current control. Movement times of approximately 450 ms finally resulted in no differences in errors between the eyes-open and eyes-closed condition. Presumably, the movement now involved only an initial impulse and no current control because visual feedback might require at least 450 ms to be processed. Vince (1948) also showed that movements shorter than 400 ms in duration could not be visually controlled.

Time to process visual feedback in controlling movement

Until the late 1960s, Woodworth's (1899) most significant finding was considered his determination of time to process visual feedback. However, his visual processing estimate of 450 ms was quite long; at least partly the result of the experimental method and the way the result was interpreted. Because of reciprocal movements, the duration of individual aiming attempts included not only the time the limb spent sliding across the paper but also the time required to reverse the direction of the movements after a previous target position had been achieved. This, as Keele and Posner (1968) argued, resulted in an overestimation of visual feedback processing time.

Rather than examining reciprocal movements, Keele and Posner (1968) had participants produce discrete movements to a target and then substantially reduced Woodworth's (1899) estimate of visual feedback processing time (i.e., 450 ms). For a series of trials, movements were performed at designated movement times ranging from 150 to 450 ms, in 100 ms increments, and on half the trials, the room lights were extinguished on movement initiation. Participants could not match the criterion movement times; the mean movement times for the light-on condition were 190, 267, 357, and 441 ms. As moving more slowly, the aiming became more accurate in the

lights-on condition. However, for the 190-ms movement time, there were no accuracy differences between the lights-on and lights-off conditions. The finding led Keele and Posner (1968) to conclude that the time required for the visual feedback loop to operate was somewhere between 190 and 260 ms. Beggs and Howarth (1970) provided additional evidence for time to process visual feedback in hand-held stylus movements under 290 ms.

Through the 1970s to 1980s, evidence was accumulating that visual feedback could be processed and used for the control of movements with latencies as short as 100 ms (e.g., Zelaznik, Hawkins, & Kisselburgh, 1983; see Carlton, 1992 for a review). Although visual processing estimates vary across different experimental manipulations and procedures, consistent is the finding that vision provides an accuracy advantage even for very rapid movements. Probably, there is no single processing time for visual feedback in controlling movements, but it depends on the specific interaction of information available and the nature of response corrections that are required. More importantly, processing delays of visual feedback have a significant implication for the model proposed by Woodworth (1899), which holds that spatial accuracy of movements depends on the time available for current control.

Clearly, Woodworth's (1899) two-component model is well-documented and essentially correct descriptions of limb control. The increase in errors as speed increases mainly resides in the current control process. In essence, visual feedback reduces spatial errors to a greater extent. Temporal constraints of the movements, however, restrict time to process visual feedback, and thus the accuracy advantage by vision gradually decreases as a function of the movement speed. Nevertheless, the model must be seen on its own level of analysis, and therefore some details need to be

revised. The first processing based model to build on Woodworth, however, did not appear until the 1960s.

Models of Speed-Accuracy Relations in Goal-Directed Movements

Fitts' law

In 1954, one of the landmark publications in the history of motor behavior research, Fitts published a systematic analysis of the relationship between speed and accuracy. His original experiment involved a now-famous Fitts paradigm (or Fitts task), in which participants tapped a hand-held stylus alternately between two target plates as rapidly as possible in 20 s. Both the width of the targets (W) and the amplitude of the movement between the targets (A) were altered from condition to condition, providing a number of possible combinations of A and W . The resulting movement time (MT) was determined as the trial duration (i.e., 20 s) divided by the number of taps completed in that time.

Fitts (1954) found that the relationship among the movement amplitude (A), the target width (W), and the resulting movement time (MT) was given by:

$$MT = a + b \left[\log_2 \left(\frac{2A}{W} \right) \right] \quad (2.1)$$

in which a and b were empirically determined constants. This logarithmic relationship has been known as *Fitts' law* in his honor and explained by the idea that the change in MT is required to meet the demands of the current control process. The “difficulty” of the movement is represented by the value $\log_2(2A/W)$ and is called the index of difficulty (ID). The more difficult is the movement by either an increase in the movement amplitude (A) or a decrease in the target width (W), the more information

has to be processed to generate the movement into the target. Because the amount of information that can be processed per unit of time is limited (Shannon & Weaver, 1949), a person compensates for a difficult combination of A and W by increasing the MT , thereby enabling the completion of the necessary processing, otherwise becoming less accurate.

Other research since the time of Fitts' (1954) original work has extended Fitts' law in number of different ways and revealed remarkable generality in a variety of contexts (see Plamondon & Alimi, 1997, for a review). For instance, in single, discrete movements, participants appeared to trade off speed for accuracy in much the same way as they did for continuous, cyclic movements (Fitts & Peterson, 1964). Recent literature (e.g., Guiard, 1993; Smits-Engelsman, Van Galen, & Duysens, 2002) has suggested that cyclic movements should not be viewed as a concatenation of discrete movements, however.

Iterative correction model

An alternative to the explanation of Fitts' law is known as the *iterative correction model*. The model was originally proposed by Crossman and Goodeve at the 1963 meeting of the Experimental Psychology Society in England. They suggested that Fitts' law could be derived mathematically on the basis of feedback control in movement with a number of assumptions. This derivation with its associated argument was described in a more accessible form by Keele (1968) and reprinted in its entirety in 1983.

Crossman and Goodeve (1963/1983) argued that movements intended to hit a target region (W) quickly and accurately were executed through iterations of feedback-based corrective submovements. Each submovement was assumed to take a constant amount of time (t) and travel a constant proportion (p) of the remaining

distance to the center of the target. Thus, the travel distances of the first, second, third, and n th submovements were pA , $pA(1-p)$, $pA(1-p)^2$, and $pA(1-p)^{n-1}$, respectively, where A was the total distance traveled and n was the number of submovements. In these expressions, $A(1-p)^{n-1}$ represented the amount of distance remaining to the center of the target at the end of the $(n-1)$ th submovement. Eventually, iterations of submovements were terminated if the remaining distance to the center of the target, thus $A(1-p)^{n-1}$ was less than $W/2$ (i.e., inside the target region). The number of submovements therefore increased in an approximately logarithmic function of A/W . The total movement time (MT) was equal to the number of submovements multiplied by the constant submovement time, and thus expressed as the same mathematical derivation as Fitts' law (Equation 2.1).

In principle, the error associated with each submovement was proportional to the remaining distance to the target (Keele, 1968) and the final endpoint accuracy was therefore dependent on the number of feedback-based corrective submovements. Again, the number of corrective submovements, and hence total movement time were related to both the movement amplitude and the target width. Put together, for a larger movement amplitude, the primary submovement would be longer and thus yield more errors, requiring more corrective submovements to secure the target. Meanwhile, a smaller target width would simply require more corrective submovements to home in on the target.

A number of recent studies, however, have shown that the iterative correction model is seriously flawed. Perhaps, the most persuasive argument against the model is based on kinematic evidence of limb trajectories (e.g., Jagacinski, Repperger, Moran, Ward, & Glass, 1980; Langolf, Chaffin, & Foulke, 1976; Meyer et al., 1988). Generally, submovements do not travel a constant proportion of the remaining

distance, nor are their times constant. More fundamentally, the model cannot explain why participants sometimes miss a target and commit an error.

Single-correction model

The *single-correction model* was put forth by Beggs and Howarth (1970, 1972). In some respects, the model resembled Woodworth's (1899) two-component model. Particularly, both models were grounded on the premise that error was reduced via the corrective process based on information about the relative positions of the limb and the target. Because vision is the most reliable information about the position of the limb and usually only the information about the position of the target, the elimination of one or both sources of information should lead to an increased target-aiming error. A number of experiments have attempted to examine this aspect and demonstrated that both limb and target information is important for aiming (e.g., Carlton, 1981b; Carson, Chua, Elliott, & Goodman, 1990).

However, a distinction should be made between a single programmed correction (Beggs & Howarth, 1970, 1972) and the type of visual homing associated with the second phase of the movement (Woodworth, 1899). Specifically, an initial ballistic movement was thought to bring the limb into the proximity of the target area, and then a single correction occurred based on visual feedback. The precision of the single correction and therefore the accuracy of the movement were dependent on the proximity of the limb to the target when the corrective movement was initiated. For longer duration movements, the limb was thought to be closer to the target when correction took place, thus explaining the speed-accuracy relations. In the meantime, visual feedback loops no longer had time to operate, and thus movements approximately less than 290 ms were assumed to be centrally controlled (Beggs & Howarth, 1972). However, this estimate of visual processing time was conflict with

the findings that visual information of the movement had accuracy benefits even if movements were made less than 110 ms (Bard, Hay, & Fleury, 1985) or vision was available only the last 25% of the movement (Carlton, 1981a). Again, visual feedback depends on the specific interaction of information available and the nature of response correction that is required.

Impulse variability model

In the wake of rather long estimates of visual processing time (e.g., Beggs & Howarth, 1972; Keele & Posner, 1968; Woodworth, 1899), Schmidt and his colleagues (Schmidt, Zelaznik, & Frank, 1978; Schmidt et al., 1979) conducted a series of experiments involved in quick, preprogrammed movements. In these experiments, participants performed rapid single-aiming movements of a stylus to a target in particular goal movement times (MT) of 140, 170, and 200 ms for either 10, 20, or 30-cm movement amplitudes (A). Errors in movements were measured as the within-participants standard deviation (SD) of the movement endpoints. In keeping with the Fitts paradigm, these errors were termed effective target width (W_e). Instead of logarithmic relations (Fitts, 1954; Fitts & Peterson, 1964), Schmidt and his colleagues demonstrated that both an increase in movement amplitude (A) and a decrease in movement time (MT) led to a linear increase in effective target width (W_e). This relation can be characterized as:

$$W_e = a + b \left(\frac{A}{MT} \right) \quad (2.2)$$

in which a and b are empirical constants. Therefore, the errors in movements (W_e) were linearly proportional to the average movement velocity (A/MT). The relationship was, however, applicable only for movements that required less than 200 ms to

complete. Presumably, for longer duration movements, there was the opportunity for feedback-based corrective processes.

The findings led Schmidt and his colleagues (1978, 1979) to a new theory, called the *impulse variability model*, which did not include a feedback-based corrective process. Two principles are of critical importance: (a) the variability in duration of muscular contractions is directly proportional to the duration, and (b) the variability in muscle forces applied is an increasing function of the force to approximately 65% of maximum, with a leveling off or slight decrease thereafter (see Sherwood, Schmidt, & Walter, 1988). These principles are of such importance because they define the variability in the two dimensions of the impulse. The impulse, forces produced over a period of time, is a critical determinant of motor action, and therefore the variability in impulses is a critical determinant of the variability in motor action. Put simply, greater forces produce faster movements or movements that cover greater distances, but inevitably greater variability in forces produces greater variability in movements.

Most of the detailed studies, however, reported non-proportional relationship between force and force variability (e.g., Newell & Carlton, 1985; Sherwood & Schmidt, 1980; Sherwood et al., 1988), questioning model's assumptions. Recently, Kim et al. (1999) demonstrated that movement variability was the product of a coherent space-time function that was driven by the nonlinear scaling of the force-time properties of the initial impulse. Specifically, the decreasing function of variable temporal errors with the increments of average velocity was complementary to the negatively accelerating function of variable spatial errors with the increments of average velocity (Newell, Carlton, Kim, & Chung, 1993).

One explanation for the non-proportional relationship between force and force variability is attributable to the mechanical properties of the moving arm. Muscle fibers shorten at specific speeds while concurrently developing force to rotate a limb segment (i.e., the force-velocity relationships). In addition, the amount of force produced by a muscle is related to the length at which the muscle is held (i.e., the force-length relationship). Furthermore, not all of the force produced by the muscle is put to use in generating rotation of the limb segment, but depending on the angle at which the joint is held (i.e., the torque-angle relationship). Visco-elastic behavior of the tendon should be taken into consideration as well because the mechanical interaction between the tendon and muscle depends on the amount of force being applied or generated, the speed of the muscle action, and the slack in the tendon (Proske & Morgan, 1987). Apparently, the muscle contraction speed, muscle and tendon length, and joint angles have a great influence on the mechanical properties of the moving arm.

Another fundamental problem is the dependency of the speed-accuracy trade-off formulation. Presumably, a linear trade-off relationship is more appropriate for time-matching tasks or temporally constrained tasks, whereas a logarithmic trade-off relationship better explains time-minimizing tasks or spatially constrained tasks. The linear and logarithmic trade-offs can be unified, however, by attributing precisely timed movements to a single pair of opposing force pulses that minimizes temporal variability, and spatially precise movements to a preprogrammed series of overlapping force pulses that increases temporal variability (Meyer, Smith, & Wright, 1982). This interpretation includes a number of assumptions about the shapes of force pulses used to produce movements and about the stochastic variation of pulses across different movements.

Overall, the impulse variability model accounts reasonably well for certain types of ballistic actions that do not require for feedback-based corrective processes. Thus, the model provides an important description of some of the centrally generated errors in goal-directed movements. The linear trade-off relationship pertains only to the initial impulse phase of the movement; however, it is also the main determinant of endpoint consistency when feedback is not available (Wallace & Newell, 1988). In the course of time, this feature provided the basis for the development of the optimized submovement model, which was proposed by Meyer and his colleagues (Meyer et al., 1988; Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

Optimized submovement model

For the last two decades, the *optimized submovement model* of Meyer et al. (1988, 1990) has been the most influential explanation of the speed-accuracy relations in goal-directed movements. Evolved from a synthesis of features of the impulse variability model and the iterative correction model, the model represents the movement production as an optimal compromise between (a) the potential endpoint variability associated with a more forceful movement and (b) the time-consuming requirements of feedback-based corrective processes.

The optimized submovement model assumes the existence of stochastic noise in the neuromotor system that may affect the primary submovement. Therefore, over a series of aiming attempts at the same target, a normal distribution of the primary submovement endpoints around the center of the target is expected. If the primary submovement lands within the target region, then the action terminates. Feedback-based corrective submovements are yet necessary if the primary submovement falls outside the target boundary. The endpoints of these corrective submovements over a series of trials are again normally distributed around the center

of the target, indicating that a correction to the correction may be required on a small proportion of trials.

Another key assumption of the model is the effect of neuromotor noise, thus a normal distribution (S_1) of the primary submovement endpoints proportionally increases with the average velocity (V_1) of the primary submovement, as expressed:

$$S_1 = KV_1 = K \frac{D_1}{T_1} \quad (2.3)$$

where K is a positive constant, D_1 is the mean distance traveled by the primary submovement, and T_1 is its mean movement time. Similarly, a normal distribution (S_2) of the corrective submovement (or secondary submovement) endpoints is given by:

$$S_2 = KV_2 = K \frac{D_2}{T_2} \quad (2.4)$$

Finally, the average total movement time ($MT: T_1+T_2$) is assumed to reflect a strategy to trade off movement speed for accuracy by optimizing the average velocities (V_1, V_2) of the primary and secondary submovements while still meeting the accuracy requirements (the target width: W). Under these assumptions, the optimized submovement model predicts that the MT is closely approximated by:

$$MT = a + b \sqrt{\frac{D}{W}} \quad (2.5)$$

where a and b are non-negative constants, and D is the total distance traveled (D_1+D_2).

This square-root approximation of the ratio D/W exhibits a shape similar to

$\log_2(2A/W)$, mimicking Fitts' law, while the standard deviations of the primary and

secondary submovement endpoints are governed by the linear trade-off functions (i.e., Equations 2.3 and 2.4). Instead, for a presence of multiple corrective submovements, a quasipower function might be a better predictor of the MT (Meyer et al., 1990):

$$MT = a + b \left(\frac{D}{W} \right)^{1/n} \quad (2.6)$$

where n is the number of corrective submovements. In general, these mathematical predictions fit the experimental data using a one-dimensional computer aiming task quite well (Meyer et al., 1988, 1990).

Since Woodworth's (1899) two-component model, of theoretical significance has been progress in describing the relation between the initial impulse and current control (e.g., Meyer et al., 1988; Schmidt et al., 1978). In particular, the magnitude of the initial impulse has a lawful relation to the dispersion of the primary submovement endpoints that defines the extent to which corrective processes (current control) must operate based on information about the relative positions of the limb and the target.

Perhaps, the optimized submovement model presents the best contemporary description of central and peripheral contributions to limb control with precision. However, recent kinematic evidence has identified several principles that have to be incorporated into current explanations of how goal-directed movements are controlled and the mechanisms responsible for the relationship between movement speed and accuracy. The advent of high-speed optoelectric technology and the development of more sophisticated computer aiming task in the 1980s have provided a great insight into a more sophisticated dual-process explanation of limb control.

Control of Goal-Directed Movements: Kinematic Evidence

Inherent errors in primary submovements

The optimized submovement model assumes the existence of stochastic noise in the neuromotor system and, as a consequence, a normal distribution of the primary submovement endpoints around the center of the target (see Slifkin & Newell, 1999 for the existence of deterministic noise). A one-dimensional computer aiming task of Meyer et al. (1988) supported the assumption. Participants produced wrist rotation to move a cursor toward a target on CRT screen, while vision of the cursor was either available over the course of aiming movements or eliminated on movement initiation. Regardless of visible or invisible cursor conditions, the endpoint variability of the primary submovements linearly increased with the average velocity of the movements. Furthermore, these inherent errors were indeed normally distributed around the center of the target.

For three-dimensional aiming movements (e.g., Carlton, 1979) or two-dimensional aiming involving the movements of a mouse on a graphic tablet (e.g., Chua & Elliott, 1993), however, a normal distribution of the primary submovement endpoints is seldom the case. Carlton (1979) reported that the primary submovements ended somewhat short of and above the target, and then followed by the corrective submovements to bring the stylus into contact with the target. Similarly, Elliott and his colleagues (e.g., Chua & Elliott, 1993; Elliott et al., 1995; Elliott, Lyons, & Dyson, 1997) demonstrated that for movements at the midline, away from the body, participants almost always undershot the target in their primary submovements.

This strategy to undershoot the target in the primary submovements is more economical on both time and energy comparing to the strategy to overshoot the target (Guiard, 1993; Smits-Engelsman et al., 2002). In case of overshooting, the limb

moves a greater overall distance before it finally comes to rest on the target. This additional distance is associated with extra time and mechanical energy, partly because the limb must overcome the inertia of zero-velocity situation at the point of reversal. From a processing point of view, the reversal in direction entails a change in the role of the muscles driving the limb. In particular, the agonist muscles become the antagonist muscles with reversal and vice versa. In this context, movement reversal has been shown to be more attention demanding than extensions to an ongoing movement made in the same direction (Brebner, 1968).

In contrast, Khan and Franks (2000) demonstrated that the primary submovements were less likely to undershoot but actually more likely to overshoot the target. Their experiment involved single-dimension, elbow-flexion movements in which one large muscle group was used to propel the limb (agonist), while another large muscle group braked the limb (antagonist). The primary submovement endpoint bias occurred when the limb reached relatively high velocities. Khan and Franks reasoned that the elastic properties of the antagonist muscle group were used to pull the limb back to its final resting position. This “spring back” behavior does not involve active control processes such as programming changes in the sequencing of agonist-antagonist activation patterns, but is caused by passive mechanical factors. Thus, in some circumstances, maintaining high velocities and overshooting the target may outweigh the benefits of slowing down the primary submovements. Regardless, errors in primary submovements are inevitable.

Feedback-based corrective processes

A number of kinematic aiming studies have recognized the importance of feedback-based corrective processes to compensate inherent errors in the primary submovements. The first investigations to incorporate a detailed kinematic analysis

were concerned with the impact of accuracy demands on movement trajectories (e.g., Langolf et al., 1976; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Soechting, 1984). These studies demonstrated that decreasing the size of the target resulted in changes to the shape of the velocity profile. Although the velocity profiles were relatively symmetric for large targets, participants spent more actual time, and therefore a greater proportional time, after peak velocity when aiming at smaller targets. Presumably, such additional time is necessary to process and use visual and kinesthetic feedback to bring the limb to rest on the target. The finding suggests the on-line regulations of movement trajectories

Studies involving the manipulation of vision have consistently shown that participants spend a greater proportion of their overall movement times after peak velocity when vision is available than occluded on movement initiation (e.g., Carson, Goodman, Chua, & Elliott, 1993; Chua & Elliott, 1993; Elliott, Carson, Goodman, & Chua, 1991). For instance, Elliott et al. (1991) had participants perform a three-dimensional aiming to a small target in a full vision condition as well as in a condition in which the room lights were extinguished on movement initiation. The latter condition eliminated vision about both the limb and the target. On some blocks of trials, movement accuracy was stressed, whereas on other blocks, participants were asked to perform as rapidly as possible. Although the impact of vision was most pronounced when attempting to be accurate, in both instructional situations the availability of vision had a clear impact on the characteristics of the movement trajectories. Specifically, participants spent more real and proportional time after peak velocity when vision was present over the course of the movement. Because errors were always greater in no-vision conditions, this extra time after peak velocity could be used to process on-line visual feedback to reduce target-aiming errors.

However, the extra time after peak velocity cannot always be attributed to discrete corrections in movement trajectories. Elliott, Binsted, and Heath (1999) had participants performed 40-cm, left-to-right aiming movements across the midline to small targets. In one condition, participants had full visual information available throughout their aiming attempt, whereas in the other condition, liquid crystal goggles were used to eliminate vision on movement initiation. Despite less target-aiming error, the vision condition exhibited no more discrete discontinuities in the movement trajectories than the no-vision condition. Although discrete adjustments to the trajectories occurred on most aiming attempts that required spatial precision, visual control might proceed in a more continuous manner with graded adjustments to the muscles being used to decelerate the movement.

Plamondon (1995a, 1995b) challenged the idea that discontinuities in movement kinematics reflected corrective processes based on the use of feedback. In his kinematic theory, spatiotemporal characteristics of movement trajectories, including corrections, are specified before the movement begins. The form of the trajectories is determined by the ratio of the agonist and antagonist muscle commands. The important assumption of the theory is that sensory feedback is not used to control movement trajectories and feedforward control emerges through practice and learning. Indeed, experiments on deafferented patients have shown that individuals without afferent feedback are capable to move (e.g., Lashley, 1917; Sanes & Jennings, 1984). Although an excellent job in describing how discontinuities occurred in the absence of feedback-based corrections, Plamondon never addressed the wealth of empirical work demonstrating that the availability of vision was one of the best predictors of movement accuracy. Numerous investigators, therefore, reported evidence and reasonable criticisms that challenged the kinematic theory (see Plamondon & Alimi,

1997). Rather, computational models suggest that the neuromuscular control system involves both feedback and feedforward control (e.g., Stroeve, 1997, 1998).

Nevertheless, Plamondon's work reinforces the idea that the presence of discontinuities in movement trajectories does not necessarily mean the presence of feedback-based corrections.

Another approach to dealing with the importance of feedback-based corrective processes is to perturb an actual movement being performed, forcing the neuromotor system to adjust to a new movement requirement. Recently, Heath, Hodges, Chua, and Elliott (1998) used a computer-based aiming task that allowed them to unexpectedly change the size and the position of the target on movement initiation. By introducing unexpected changes, Heath et al. could dissociate prior planning processes from on-line control in an attempt to examine the limits of corrective processes. Of particular interest in these perturbed situations was whether the movement kinematics was a function of the original target or the new target. Although the early movement kinematic landmarks (e.g., peak velocity and time to peak velocity) were dependent on the size and the movement amplitude associated with the original target, time spent after peak velocity, and therefore overall performance was determined by the accuracy demands imposed by the new target. The finding again indicates the on-line regulations of movement trajectories.

A more recent perturbation study of Desmurget et al. (1999) provided unique insight into the on-line regulation of movement trajectories. Participants moved the unseen right hand to a visual target that either remained stationary or slightly moved during saccadic eye movements. Under normal circumstances, participants rapidly adjusted their movement trajectories to meet the demands by the new target. However, when transcranial magnetic stimulation (TMS) was applied over the left posterior

parietal cortex during target presentation, corrections to their movement trajectories failed to occur. In dealing with the neurophysiological correlates of limb control, this specific cortical region appeared to be at least partly responsible for the homing phase of the movements. Indeed, posterior parietal cortex has been established to play an important role in the visual regulation of movements (see Milner & Goodale, 1995 for a review).

Kinematic evidence on goal-directed movements shows that the initial portion of the movements is specified prior to movement initiation and sensitive to the task requirements. As the limb approaches the target, deceleration often occurs quite slowly, particularly if the accuracy requirements of the movement are high. This deceleration profile reflects on-line adjustments to the movement trajectory based on sensory feedback and is more prevalent in the presence of vision. Perhaps, goal-directed movements are optimized by being proficient at central planning and, at least as importantly, being efficient at on-line feedback processing.

Optimality in Goal-Directed Movements

Changes in the role of vision with practice

A traditional proposition, the idea of *closed-loop to open-loop transition* has been advanced on the issue regarding the relative importance of on-line feedback processing in controlling movements. According to this proposition, with practice, a performer becomes progressively less dependent on the sources of afferent information (e.g., Pew, 1966; Schmidt & McCabe, 1976). In particular, the importance of on-line vision gradually decreases as learning progresses. The assumption is that during early practice, learners use feedback (closed-loop control) to develop central

representations that allows the movement to be carried out without feedback but with only feedforward processes (open-loop control) later in learning.

Pew's (1966) visual tracking study is frequently cited as evidence for this proposition. Participants were required to align a dot shown on a cathode ray tube with a central target by successively pressing keys with the index finger of each hand. Pressing the right button caused the dot to accelerate to the right, whereas pressing the left button caused the dot to accelerate to the left. Early in practice, relatively long intervals (458 ms) between key-presses were observed. Supposedly, the participants waited for visual information about the movement of the dot before initiating the next key-press. Yet, late in practice, a very different pattern of key-presses emerged where short interresponse delays (292 ms) were observed. This interresponse time reduction was generally interpreted as an indication that with practice, the participants shifted from closed-loop to open-loop control. A coincident timing study of Schmidt and McCabe (1976) provided additional evidence for the closed-loop to open-loop transition. Empirical support for this proposition is yet limited. Rather, a number of recent studies have demonstrated that a large part of motor skill development involves learning to use on-line afferent information rapidly and efficiently.

The strongest evidence for a more efficient, less time-consuming feedback loop comes from a number of aiming studies conducted by Proteau and his colleagues (Proteau & Cournoyer, 1990; Proteau et al., 1987; Proteau, Marteniuk, & Lévesque, 1992; see Proteau, 1992 for a review). In their original study (Proteau et al., 1987), participants practiced a 90-cm manual aiming task for either 200 or 2,000 trials with vision of both the target and the performing limb. Following acquisition, participants completed a transfer test in which vision of the performing limb was eliminated on movement initiation and thus only vision of the target was available. In transfer, the

removal of vision of the performing limb resulted in a significant increase in aiming errors regardless of the number of acquisition trials (200 or 2,000 trials). More importantly, the aiming errors were greater after extensive practice (2,000 trials) than moderate practice (200 trials). The findings clearly demonstrated that participants became progressively more dependent on the sources of afferent information, leading to the alternative proposition known as the *specificity of practice hypothesis* (Proteau, 1992). Besides Proteau and his colleagues, other researchers (e.g., Elliott & Jaeger, 1988; Khan, Franks, & Goodman, 1998) have also reported supporting this hypothesis (cf. Pratt & Abrams, 1996).

The latest version of the specificity of practice hypothesis views learning as the construction of sensorimotor representations within the central nervous system that becomes increasingly proficient at central planning and controlling highly practiced movements (Ivens & Marteniuk, 1997). More specifically, a source of afferent information most likely to ensure optimal performance would quickly be determined and progressively dominate all other sources of information (Tremblay & Proteau, 1998). Optimal aiming performance is generally attributed to the availability of on-line visual feedback. With learning, the reliance on vision increases, and thus the withdrawal of vision results in an increase in aiming errors. This situation refers to a *specificity of practice effect* (see Proteau, 1992) and creates the difficulty for models of limb control that minimize the overall importance of response-produced feedback (e.g., Pew, 1966; Plamondon, 1995a, 1995b).

However, on-line vision appeared to be less useful in ensuring optimal performance when aiming at a smaller target (Proteau & Isabelle, 2002), variable practice schedule (Tremblay, Welsh, & Elliott, 2002), uncertainty of vision availability (Khan et al., 2002), or vision use constraint (Elliott, Ricker, & Lyons,

1998), and therefore, its withdrawal became less detrimental. Evidence indicated that the relative efficiency of visually-guided error corrections mediated how exclusively individuals relied on vision in controlling movements.

Changes in control strategies with practice

Most recently, investigators have paid much attention to the control strategies that individuals adapt to optimize performance in goal-directed movements. An issue at the forefront of much investigating concerns the relative contributions of central planning and on-line feedback processing in controlling movements. Specifically, how practice at a rapid aiming task changes the component submovements is of a primary interest.

Early contributions to this issue were somewhat inconsistent. For instance, Abrams and Pratt (1993) showed that practice improved overall movement time, but had different effects on the individual submovements. In particular, participants reduced the amount of time spent performing the corrective submovements, but actually, they slightly increased the time needed to produce the primary submovement. The finding indicated that practice primarily enhanced the ability to use on-line feedback. In contrast, Pratt and Abrams (1996) reported that the practice-related changes in rapid aiming movements arose from improved programming of the initial impulse and not from improved efficiency of feedback processing. Nevertheless, the availability of vision had little impact on how practice affected the component submovements. In the meantime, kinematic data of Khan et al. (1998) over 2,000 trials indicated that learning involved both an improvement in the organization of the initial impulse and an improvement in the feedback-based corrective processes. Furthermore, different control strategies emerged between visual feedback conditions.

Despite an inconsistency in early findings, a number of recent studies demonstrated that with practice, participants progressed toward a control strategy that was dependent on their abilities to use on-line visual feedback (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003). When vision was available, participants planned their movements to use it. With the reliance on this effective source of afferent information, they increased the velocity of the primary submovement to bring the limb to the vicinity of the target quickly. Although faster movements led to greater variability in movement endpoints, this strategy granted more time available for visual feedback utilization in the corrective submovements. By contrast, participants without vision produced a slower, but less variable primary submovement to abandon visually-guided error corrections. The findings suggest optimality in goal-directed movements through a reciprocal interplay between central planning and on-line feedback processing.

In addition to on-line regulation of movement trajectories, Khan and Franks (2003) revealed that participants processed visual information off-line to improve their programming of the initial impulse. As Ghez, Gordon, Ghilardi and Sainburg (1995) pointed out, vision about the relative position of the limb and the target during movements may be needed quite frequently to calibrate other sensory and motor systems (e.g., proprioceptions). This off-line use of vision for better planning of movements made participants possible to minimize their endpoint variability of the primary submovements as a function of practice (Khan & Franks, 2000, 2003). In line with the specificity of practice hypothesis, however, the removal of vision resulted in an increase in variability of the primary submovement endpoints, indicating the increased reliance on vision.

In our current understandings, visual information, serving both a feedback and feedforward function, ensures optimal aiming performance. Learning at goal-directed movements thus involves an optimal use of vision by adapting control strategies. Consequently, a performer becomes better at both structuring the appropriate initial impulse and using on-line feedback to correct errors inherent in the movements. Depending on the abilities to use on-line visual feedback and levels of practice, however, different control strategies are possible to optimize performance in goal-directed movements.

Summary

In the present chapter, comprehensive account of numerous details in goal-directed movements was provided through an existing extensive body of research. Following Woodworth (1899), the empirical work over the past century has demonstrated that a movement toward a target consists of two components, an initial impulse followed by current control. In attempts to further elaborate the control processes underlying these two components of goal-directed movements, researchers have studied, in detail, movement planning, corrective processes, time to process feedback, impulse variability, and so forth. Amongst the empirical and theoretical contributions, following three are critically important in describing and explaining how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy; (a) the magnitude of the initial impulse has a lawful relation to the dispersion of the primary movement endpoints, (b) visual feedback reduces spatial errors to a greater extent as temporal constraints of the movements, (c) optimality in goal-directed movements

occurs through a reciprocal interplay between central planning and on-line feedback processing.

Despite empirically and theoretically significant to the literature, existing evidence and supports are based mainly on behavioral and kinematical analyses, but seldom on dynamical analyses. Kinematical analyses, however, only quantify the resultant movements, and thus the necessity to deal with the mechanical causes of goal-directed movements is highly stressed. In multi-joint movements, the motion of a particular segment affects other segments in a kinetic chain, and thus the completely different limb dynamics but the same limb kinematics would be possible. In literature, the accommodations to these motion-dependent effects were evident (e.g., Gribble & Ostry, 1999; Heise & Cornwell, 1997; Hirashima et al., 2003; Hoy & Zernicke, 1986; Schneider et al., 1989). Perhaps, a method of the intersegmental dynamics is capable of providing further evidence on how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy.

CHAPTER III INTERSEGMENTAL DYNAMICS

Traditionally, motor performance has been measured in possible outcome scores (e.g., aiming error and movement time) and kinematic profiles (e.g., displacement, velocity, and acceleration). Dynamical analyses are, however, inevitable to quantify the mechanical causes of movements. The reason is that in addition to those forces arising from muscle contractions, limb trajectories can be influenced by gravitational forces and passive limb reactions to muscle actions. The passive reactions of the limb include inertial, Coriolis, and centripetal forces, as well as those from various connective tissues. Limbs are systems of linked bodies, and thus the motion of any one segment exerts forces on the remaining parts of the linkage. Those passive-interactive forces can act on other segments in a kinetic chain, even if a given segment is not exposed to active muscle forces. In Bernstein's (1967) view, with respect to the control of active and passive forces, ". . . the secret of co-ordination lies not only in not wasting superfluous force in extinguishing reactive phenomena but, on the contrary, in employing the latter in such a way as to employ active muscle forces only in the capacity of complementary forces" (p. 109).

Kinematical analyses only quantify the resultant movements, and therefore the necessity to deal with the mechanical causes of goal-directed movements is highly stressed to further elaborate our current knowledge. The way in which limb trajectories are influenced by these complex combinations of forces is a difficult but tractable in rigid-body dynamics. In particular, a method of the *intersegmental dynamics* is possible to examine the motion-dependent interactions between segments.

In the present chapter, the fundamentals and applications of the intersegmental dynamics are discussed in relation to the task used in this study. Note that a bold font indicates variables representing vectors, otherwise scalars.

Fundamentals

Kinematic coupling

This study concerns a hand-held stylus movement to a target involving motions at the shoulder, elbow, and wrist joints (Figure 3.1a, see Figure 4.1c for the overhead view of the experimental setup). The displacement of the stylus (d_{stylus}) is, therefore, determined by the cumulative motion of all the involved body segments (i.e., the upper arm, forearm, and hand), and is given by:

$$d_{stylus} = d_{m/w} + d_{w/e} + d_{e/s} + d_s \quad (3.1)$$

where $d_{m/w}$ refers to the displacement of the metacarpophalangeal joint (m) relative to the wrist joint (w), and the subscripts e and s represent the elbow and shoulder joint, respectively.

Likewise, other kinematic profiles of the stylus depend on the relative kinematics of each segment and the absolute kinematics of the shoulder joint. Based on the relation between linear and angular velocity (ω) (Figure 3.1b) as well as acceleration (α) (Figure 3.1c), the linear velocity (v_{stylus}) and acceleration (a_{stylus}) of the stylus can be written as:

$$v_{stylus} = r_h \omega_h + r_f \omega_f + r_u \omega_u + v_s \quad (3.2)$$

$$a_{stylus} = \sqrt{(r_h \omega_h^2)^2 + (r_h \alpha_h)^2} + \sqrt{(r_f \omega_f^2)^2 + (r_f \alpha_f)^2} + \sqrt{(r_u \omega_u^2)^2 + (r_u \alpha_u)^2} + a_s \quad (3.3)$$

where r indicates the length of each segment, and the subscripts h , f , and u represent the hand, forearm, and upper arm, respectively.

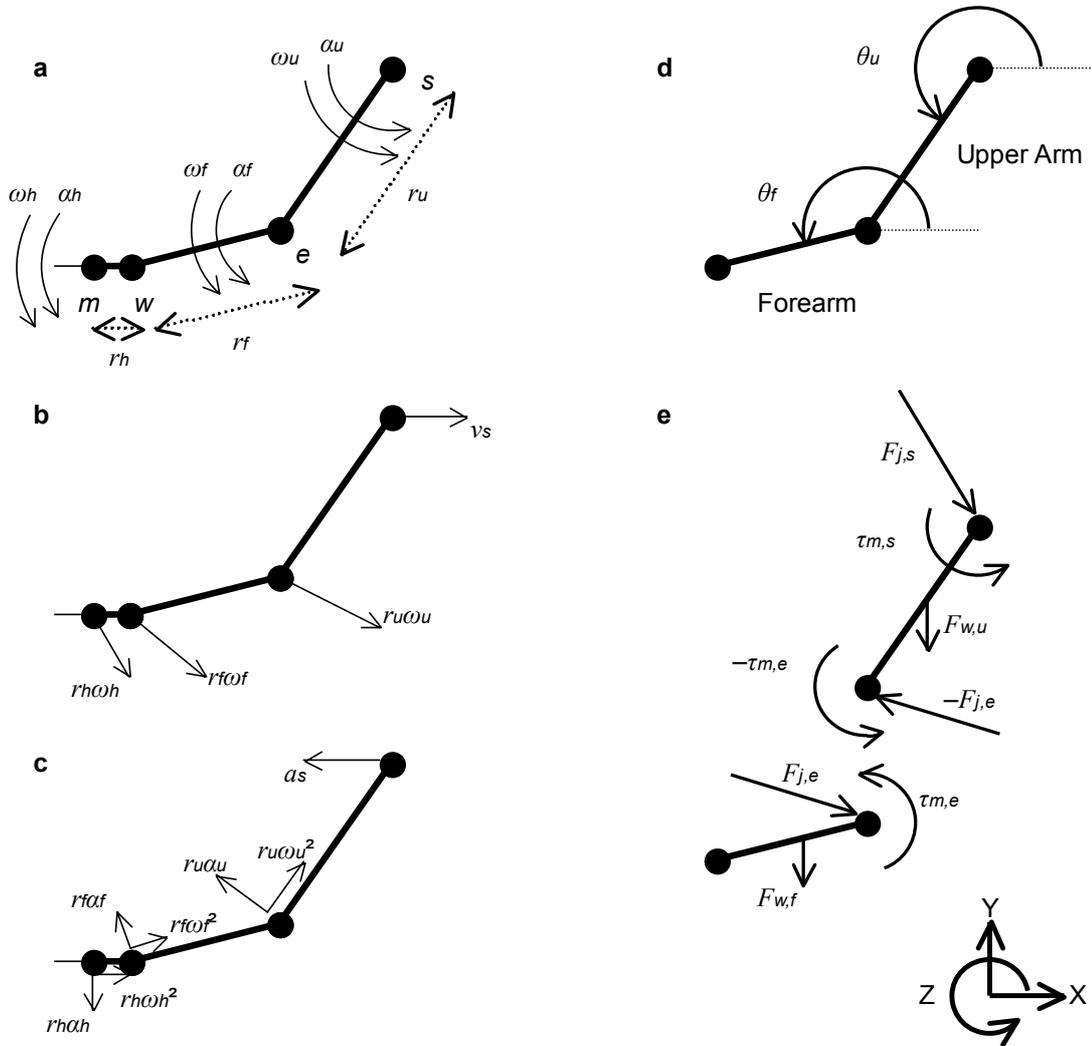


Figure 3.1. Kinematics and Dynamics of a hand-held stylus movement to a target involving motions at the shoulder, elbow, and wrist joints. (a) The length (r), angular velocity (ω), and angular acceleration (α) of the hand (h), forearm (f), and upper arm (u). (b) The relation between linear and angular velocity. (c) The relation between linear and angular acceleration. (d) The position of the forearm and upper arm. (e) The free body diagram of the forearm and upper arm. Each segment has a weight vector ($F_{w,u}$ and $F_{w,f}$), a resultant joint force ($F_{j,s}$ and $F_{j,e}$), and a resultant muscle torque ($\tau_{m,s}$ and $\tau_{m,e}$). m = the metacarpophalangeal joint, w = the wrist joint, e = the elbow joint, s = the shoulder joint.

An important feature of Equation 3.3 is that the acceleration of each segment in the system is influenced by the acceleration of all the other segments. This kinematic coupling between segments occurs because of the dynamics interactions between segments.

Motion-dependent effects

As an example of the dynamics interactions, the motion-dependent effects between the upper arm and the forearm moving on the vertical plane are considered. The two-segment system and its orientation are defined by four coordinates: the x- and y-coordinates of the shoulder (s), and the angles of the upper arm (θ_u) and the forearm (θ_f) (Figure 3.1d). Each segment has a weight vector ($\mathbf{F}_{w,u}$ and $\mathbf{F}_{w,f}$). In addition, there are resultant joint forces ($\mathbf{F}_{j,s}$ and $\mathbf{F}_{j,e}$) as well as resultant muscle torques ($\boldsymbol{\tau}_{m,s}$ and $\boldsymbol{\tau}_{m,e}$) acting about the shoulder and elbow joints (Figure 3.1e). Then, the equation of motion for the forearm is expressed as:

$$\sum \mathbf{F} = m\mathbf{a}, \quad \mathbf{F}_{j,e} + \mathbf{F}_{w,f} = m_f \mathbf{a}_f \quad (3.4)$$

where m_f is the mass of the forearm and \mathbf{a}_f is the linear acceleration of the forearm center-of-mass (CM). Because of a linked two-segment system, \mathbf{a}_f can be expressed in the form of Equation 3.3:

$$\mathbf{a}_f = \mathbf{a}_s + (\boldsymbol{\alpha}_u \times \mathbf{r}_{e-s}) + (\boldsymbol{\omega}_u \times \boldsymbol{\omega}_u \times \mathbf{r}_{e-s}) + (\boldsymbol{\alpha}_f \times \mathbf{r}_{f-e}) + (\boldsymbol{\omega}_f \times \boldsymbol{\omega}_f \times \mathbf{r}_{f-e}) \quad (3.5)$$

and this expression (Equation 3.5) can be inserted into Equation 3.4 to rearrange for the resultant joint force about the elbow joint ($\mathbf{F}_{j,e}$):

$$\begin{aligned} \mathbf{F}_{j,e} = & m_f \mathbf{a}_s + m_f (\mathbf{a}_u \times \mathbf{r}_{e-s}) + m_f (\boldsymbol{\omega}_u \times \boldsymbol{\omega}_u \times \mathbf{r}_{e-s}) \\ & + m_f (\mathbf{a}_f \times \mathbf{r}_{f-e}) + m_f (\boldsymbol{\omega}_f \times \boldsymbol{\omega}_f \times \mathbf{r}_{f-e}) - \mathbf{F}_{w,f} \end{aligned} \quad (3.6)$$

where the subscripts $e-s$ and $f-e$ represent the distance from the elbow to the shoulder, and the distance from the forearm CM to the elbow, respectively.

In the next step, the resultant muscle torque about the elbow joint ($\boldsymbol{\tau}_{m,e}$) can be expressed using the moment-of-force equation for the forearm about the transverse axis through the CM:

$$\sum \boldsymbol{\tau}_{g,f} = I_{g,f} \boldsymbol{\alpha}_f, \quad \boldsymbol{\tau}_{m,e} + (\mathbf{r}_{f-e} \times \mathbf{F}_{j,e}) = I_{g,f} \boldsymbol{\alpha}_f \quad (3.7)$$

where $I_{g,f}$ represents the moment of inertia of the forearm about the transverse axis through the CM. Finally, Equation 3.6 is inserted into Equation 3.7 to rearrange for $\boldsymbol{\tau}_{m,e}$, with changes in the expression from vector to scalar variables:

$$\begin{aligned} \tau_{m,e} = & (r_f \cos \varphi m_f l_u \alpha_u) && [r\alpha \text{ of upper arm}] \\ & + (r_f \sin \varphi m_f l_u \omega_u^2) && [r\omega^2 \text{ of upper arm}] \\ & + (r_f^2 m_f l_f \alpha_f) && [r\alpha \text{ of forearm}] \\ & + (r_f \sin \theta_f m_f a_x + r_f \cos \theta_f m_f a_y) && [a \text{ of shoulder}] \\ & + (I_{g,f} \alpha_f) && [\text{forearm inertial torque}] \\ & + (r_f \cos \theta_f m_f g) && [\text{forearm weight}] \end{aligned} \quad (3.8)$$

where φ is the elbow angle ($\theta_f - \theta_u$), r_f is the distance from the elbow to the forearm CM, and g is the gravitational constant. This final equation (Equation 3.8) indicates that the resultant muscle torque about the elbow joint can be expressed in terms of five motion-dependent effects and one gravity-dependent effect (forearm weight).

Similar procedures can be used for other linked segments (i.e., the upper arm and hand) (see Enoka, 2002 for a detail). Figure 3.2 presents an exemplar time series of net joint moment and its components at the elbow during rapid aiming movements used in this study (see Chapter 5 and Appendix A for specific details).

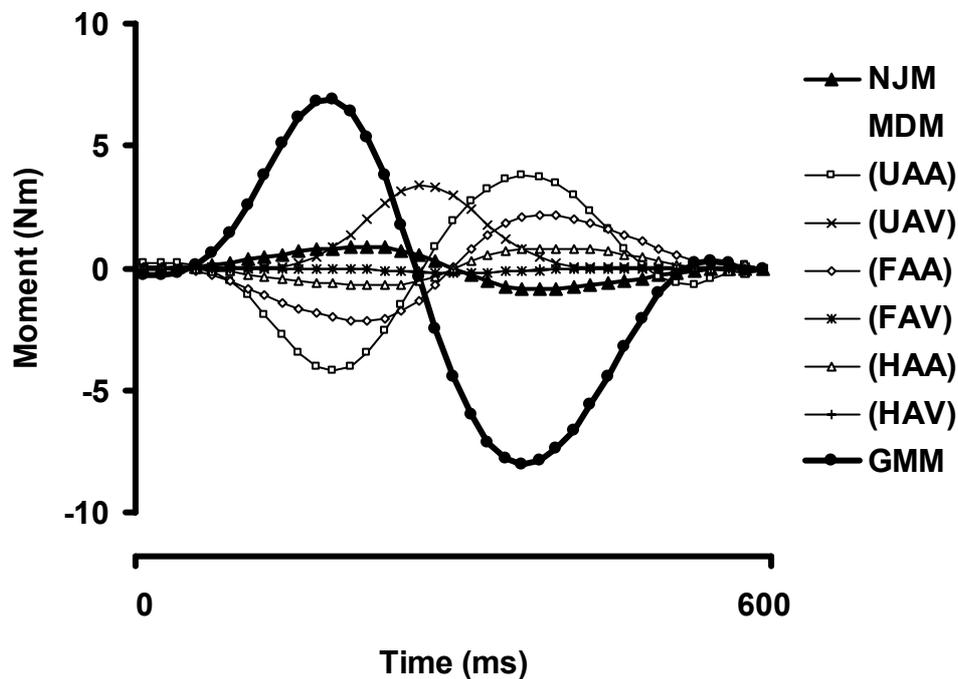


Figure 3.2. An exemplar time series of net joint moment and its components at the elbow during rapid aiming movement. NJM = net joint moment; MDM = motion-dependent moment; UAA = moment due to upper arm angular acceleration; UAV = moment due to upper arm angular velocity; FAA = moment due to forearm angular acceleration; FAV = moment due to forearm angular velocity; HAA = moment due to hand angular acceleration; HAV = moment due to hand angular velocity; GMM = generalized-muscle moment. No gravity-dependent moment because of the movement in the horizontal plane. Positive values indicate elbow extension, while negative values indicate elbow flexion.

Applications

Empirical findings in motor control

The intersegmental dynamics analysis has been used to evaluate motor control questions by examining various well learned skills, such as reaching (Hollerbach & Flash, 1982), running (Phillips, Roberts, & Huang, 1983), and kicking (Putnam, 1991). A general conclusion that can be made from these studies is that the motion of a particular body segment can exert significant torques on the other segments in the system, particularly for whole-limb, rapid movements. Hollerbach and Flash (1982) suggested that the neuromuscular system must consider these significant passive reactions during movements and therefore this type of information should be addressed in theories of motor control.

In literature, the accommodations to these motion-dependent effects were evident (e.g., Gribble & Ostry, 1999; Heise & Cornwell, 1997; Hirashima et al., 2003; Hoy & Zernicke, 1986; Schneider et al., 1989). Schneider et al. (1989) revealed the exploitation of the passive-interactive properties of the moving system with practice. Hirashima et al. (2003) recently showed that participants adjusted the speed and accuracy of ball-throwing by utilizing interaction torque or compensating for it. Studies on patients with nervous-system injury have indicated that these accommodations are essential for the execution of the accurate multi-joint movements. For instance, cerebellar patients could not deal with the interaction torque appropriately, and as a consequence, an abnormally-curved hand path in reaching movements was produced (Bastian et al. 1996). Mechanisms underlying the intersegmental dynamics were demonstrated by a three-stage control system (Sainburg et al., 1999), reliance on proprioceptive feedback (Sainburg et al., 1995),

and independent learning of internal models for kinematic and dynamic control (Krakauer, Ghilardi, & Ghez, 1999).

Implications for rapid aiming movements

In multi-joint aiming task, neural-processing transforms visuospatial information about the initial hand position and the target location into motor commands to specify muscle forces and joint motions that move the hand to the desired location (Desmurget et al., 1998). This perceptual-motor transformation needs to take the dynamic properties of the moving arm into consideration because the *net joint* moment, which is proportional to the angular acceleration at the joint, is represented as the sum of the *generalized-muscle*, *gravity-dependent*, and *motion-dependent* moments.

Nevertheless, how visual feedback is used in controlling the intersegmental dynamics and the ways that this input may change as a function of practice are still not fully understood. Among several sources of afferent (or exteroceptive) information, proprioceptive feedback has been shown critical for developing internal models of the intersegmental dynamics (e.g., Gordon et al., 1995; Sainburg et al., 1999; Sainburg et al., 1995). However, vision could substitute to some extent for the loss of proprioception (Ghez, Gordon, & Ghilardi, 1995). Rather, visual dominance over proprioception occurred with practice (Hirata & Yoshida, 2000). Investigations into the mechanical causes of goal-directed movements would provide some insight into the role of visual feedback in ensuring optimal performance.

A limitation on studies focusing on kinematical analyses (e.g., Fitts, 1954; Khan et al., 2002; Khan & Franks, 2000; Meyer et al., 1988; Woodworth, 1899) is also emphasized. These studies assume that faster movements are associated with greater force. The assumption is generally true, but in essence, the completely

different limb dynamics but the same limb kinematics would be possible in multi-joint movements. Besides forces arising from muscle contractions, passive limb reactions to muscle actions are significant to limb trajectories. Studies merely manipulating kinematic parameters, however, cannot account for these motion-dependent effects. By contraries, the intersegmental dynamics is useful to estimate the active and passive contributions to the movement trajectories.

The present chapter discussed the fundamentals and applications of the intersegmental dynamics. Clearly, analyses of the intersegmental dynamics are inevitable to provide further evidence on how goal-directed movements are controlled and what are the mechanisms responsible for the relationship between movement speed and accuracy.

CHAPTER IV

EXPERIMENT 1: INHERENT ERRORS

In moving a limb from one position to another, spatial accuracy of the movement systematically decreases as speed of the movement increases, and vice versa (e.g., Fitts, 1954; Woodworth, 1899). Such a trade-off between speed and accuracy is a natural feature of human motor behavior and thus a fundamental concern in motor control. Empirical findings have clearly demonstrated that on-line visual feedback plays an important role for movement modifications and error corrections (e.g., Meyer et al., 1988; Woodworth, 1899). However, this accuracy advantage by vision gradually decreases as a function of movement time (i.e., movement speed) because temporal constraints of movements restrict time to process visual feedback (Keele & Posner, 1968). As a result, visually-guided error corrections become ineffective, and thus spatial variability in movements increases.

Rather than investigating timing requirements of corrective processes, the present chapter focuses on inherent errors in rapid aiming movements. The existing models of goal-directed movements (e.g., Meyer et al., 1988; Schmidt et al., 1979) predict that the amount of movement variability increases as the level of force output increases. Evidence was consistent; in particular, variable errors in participants' movement endpoint increased as a function of movement speed (e.g., Fitts, 1954; Kim et al., 1999; Meyer et al., 1988; Schmidt et al., 1979; Woodworth, 1899). Although one could move faster, greater force led to greater variability in force and thus greater variability in movements.

A limitation for the findings was yet apparent because these studies merely manipulated kinematic parameters of goal-directed movements (e.g., movement speed and limb velocity). The assumption was that faster movements were associated with greater force. In multi-joint movements, however, the motion of a particular segment affects other segments in a kinetic chain, and thus the completely different limb dynamics but the same limb kinematics would be possible. Some caution is therefore warranted before one examines the mechanical causes of movements.

In the context, this experiment examined spatial accuracy of rapid aiming movements by differentiating limb dynamics while keeping limb kinematics constant. As a number of studies demonstrated, spatial errors in movements would increase with the average velocity of the movements. Furthermore, a lawful relation between errors and active contributions to the movement trajectories was expected if the level of force output was a primary determinant of the movement variability (e.g., Meyer et al., 1988; Schmidt et al., 1979).

Method

Participants

Five male university students with no neuromuscular disorders or functional limitations in their left arms (testing arms) participated in this experiment. All participants had normal or corrected-to-normal vision and signed an institutionally approved informed consent prior to testing. The experimental protocol was approved by the School of Human Sciences Ethical Committee at Waseda University.

Task, apparatus, and procedure

The task was an 80-cm rapid aiming movement involving motions at the shoulder, elbow, and wrist joints. Participants were instructed to lift a hand-held stylus

from a home position, move their left arm in a backhand motion, and strike the stylus on a target (3 cm in diameter and 80 cm distance away) as accurately as possible with three temporal constraints: 300, 400, and 500 ms. Aiming movements were performed while lying face either left or right on a flat bench to differentiate limb dynamics yet to keep limb kinematics constant (Figure 4.1). The vertical plane movements were therefore either (a) downward movements with gravity (DM) or (b) upward movements against gravity (UM).

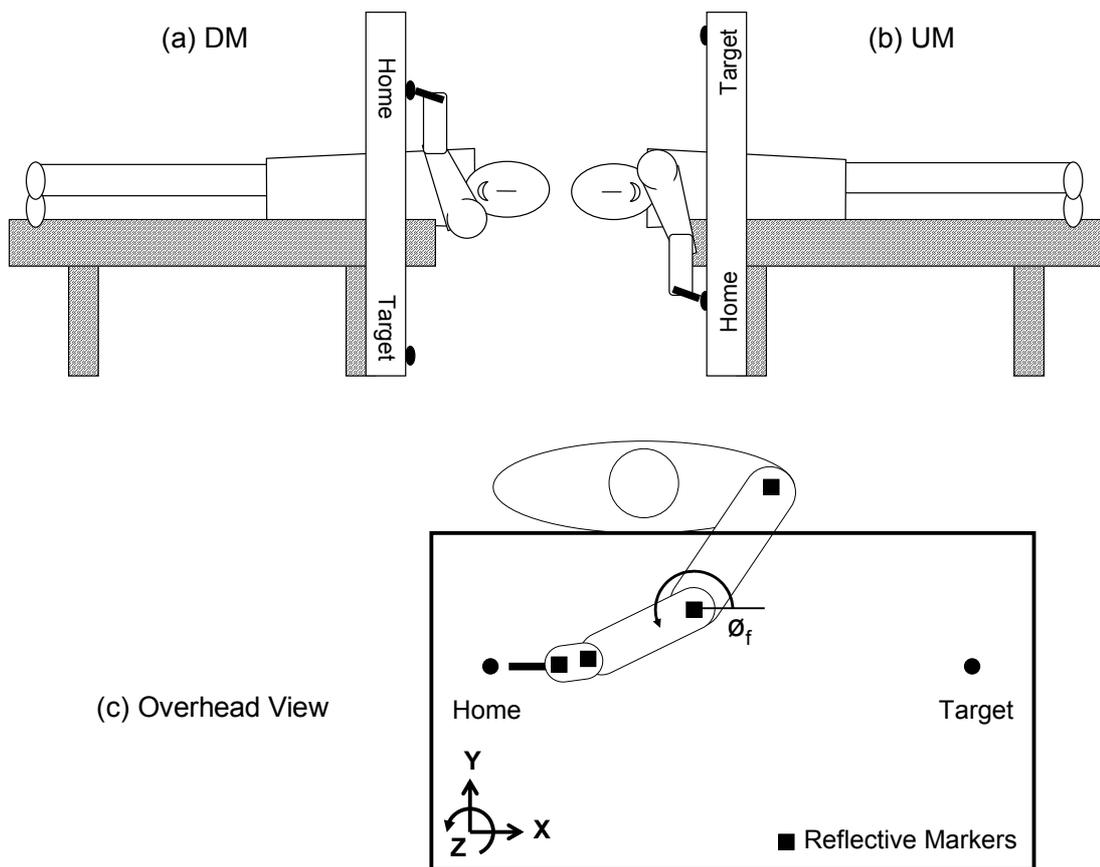


Figure 4.1. The experimental setup. (a) Downward movements with gravity (DM); (b) Upward movements against gravity (UM). (c) Overhead view. Axes indicate positive directions for kinematic and kinetic measures (convention for the forearm segment angle is shown as an example).

After becoming comfortable at the task and test conditions, participants completed 10 trials in each condition before switching to other conditions. Presentation order of the testing conditions was counterbalanced across participants. At the beginning of each trial, participants started with a stylus at the home position, and then initiated their movement at any time without regard to minimizing reaction time. The target was located on a graphic tablet (intuos2, WACOM) so that a point of contact of the stylus was easily detected. At the end of each trial, the point of contact of the stylus relative to the target as well as the flight time of the stylus from the home position to the target were visually presented on a computer screen.

Highly reflective, spherical markers were attached to participants' left arm (moving arm) to represent the locations of the shoulder, elbow, wrist, and metacarpophalangeal (MP) joints (see Figure 4.1c). The motion of these markers was recorded with a high-speed video camera (RGB-Rabbit-2, Photoron) operating at 250 Hz, and digitized with a video-based motion analysis system (FrameDiasV3, DKH) for X and Y coordinates. Coordinate data were then filtered using a low-pass, zero-lag, Butterworth digital filter with a cut-off frequency of 8.0 Hz, and used to determine the two-dimensional limb kinematics and dynamics in the primary plane of motion (i.e., the vertical plane). Limb movements were not mechanically constrained in two-dimensions, however, only the vertical movements were analyzed given the small number of out-of-plane deviations.

Data reduction: Intersegmental dynamics

Prior to data collection, anthropometric measures (e.g., length, circumference, and breadth) of participants' left arm were taken to estimate body segmental mass, center of mass (CM) location, and moment of inertia about the transverse axis through the CM (Clauser, McConville, & Young, 1969; Hinrich, 1985) (see Appendix B for

regression equations for moment of inertia). The average segmental parameters for participants were: (a) upper arm (mass = 1.7 ± 0.3 kg; CM from proximal joint = 14.6 ± 0.6 cm; moment of inertia = $6.9 \pm 2.2 \times 10^{-3}$ kg·m²); (b) forearm (mass = 1.1 ± 0.2 kg; CM from proximal joint = 9.7 ± 0.6 cm; moment of inertia = $5.1 \pm 1.5 \times 10^{-3}$ kg·m²); and (c) hand (mass = 0.5 ± 0.1 kg; CM from proximal joint = 8.9 ± 0.0 cm; moment of inertia = $7.8 \pm 1.0 \times 10^{-4}$ kg·m²).

The arm was modeled as three linked segments with frictionless hinge joints and the trunk was stationary. At the shoulder and elbow, net joint moment (NJM) and its three moment components about the rotational axis (i.e., Z axis) were calculated using equations of motion presented by Schneider et al. (1989) (see Chapter 3 and Appendix A for specific details). The three moment components were: (1) generalized-muscle moment (GMM) – moment arising from active muscle forces and other soft tissue forces crossing the joint; (2) motion-dependent moment (MDM) – moment arising from passive-interactive forces by dynamic interactions between segments; and (3) gravity-dependent moment (GDM) – moment arising from gravitational forces. NJM was the sum of all positive and negative components from categories (1), (2) and (3), and directly proportional to limb acceleration profiles. While NJM, MDM, and GDM were directly calculated from the limb kinematics, GMM was a residual term; in particular, the sum of GMM, MDM and GDM equaled NJM.

Data analyses: Dependent measures

To evaluate overall performance, movement time (MT) and root mean square error (RMSE) of aiming accuracy were computed. MT was defined as the flight time of the stylus from the home position to the target, whereas aiming accuracy was defined as radial distance between the center of the target and the point of contact of

the stylus. Because the accuracy distributions were not normal, the RMSE scores were transformed to $\ln(\text{RMSE})$ by taking the natural log of the data. Each dependent measure was separately compared with a 2 (Test Condition: DM and UM) $\times 3$ (Temporal Constraint: 300, 400, and 500 ms) repeated measures analysis of variance (ANOVA). If necessary, paired- t tests were used for pairwise mean comparisons. All statistical tests were conducted with alpha set at .05.

Results and Discussion

Limb kinematics and dynamics

Figures 4.2 and 4.3 present an exemplar time series of limb kinematics and dynamics at the shoulder and elbow, respectively, during rapid aiming movements for a representative participant. An analysis of the intersegmental dynamics revealed that an 80-cm hand-held stylus movement with gravity (i.e., DM) and against gravity (i.e., UM) yielded nearly identical limb kinematics (i.e., angular displacement, velocity, and acceleration), but completely different limb dynamics. In DM, gravity (i.e., GDM) acted as a limb extensor, and therefore assisted in accelerating yet resisted in decelerating the limb to a target. In UM, on the other hand, gravity acted as a limb flexor, and therefore resisted in accelerating yet assisted in decelerating the limb to a target (see Figures 4.2d and 4.3d). As a consequence, UM required greater active muscle forces (i.e., GMM) in the acceleration phase, while DM required greater active muscle forces in the deceleration phase (see Figures 4.2e and 4.3e).

Strictly, however, muscle activation profiles during the movements were somewhat different between DM and UM. In particular, to clamp the limb at a home position, limb flexor muscles were isometrically activated in DM; whereas limb extensor muscles were in UM. Upon the movement onset, extensor muscle activities

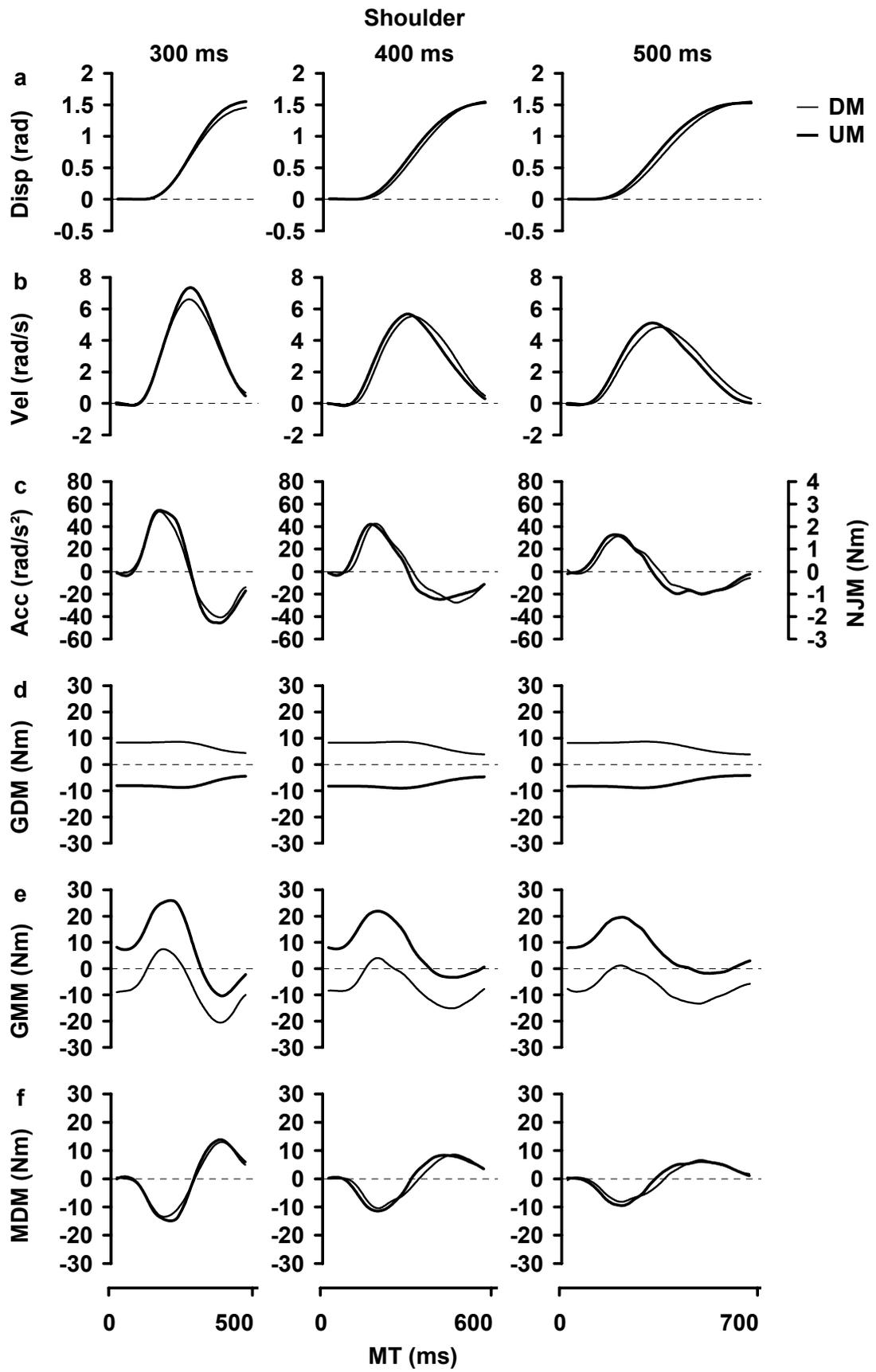


Figure 4.2. An exemplar time series of limb kinematics and dynamics at the shoulder during rapid aiming movements for a representative participant, plotted as a function of test conditions: (DM) downward movements with gravity, (UM) upward movements against gravity; and temporal constraints: 300 ms at the *left*, 400 ms at the *middle*, 500 ms at the *right*. (a) Angular displacement; (b) Angular velocity; (c) Angular acceleration and NJM = net joint moment; (d) GDM = gravity-dependent moment; (e) GMM = generalized-muscle moment; (f) MDM = motion-dependent moment. Positive values indicate shoulder horizontal abduction, while negative values indicate shoulder horizontal adduction.

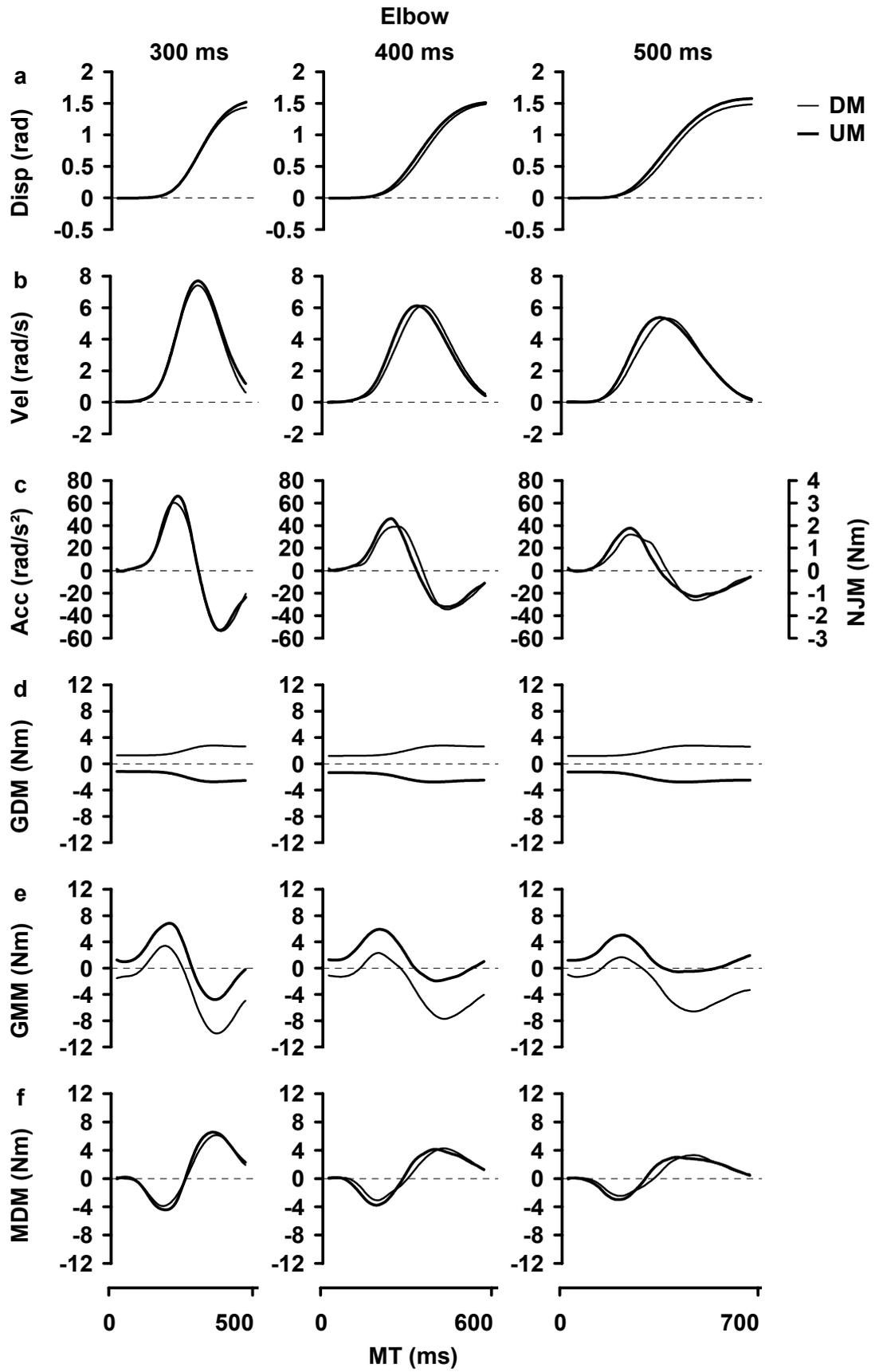


Figure 4.3. An exemplar time series of limb kinematics and dynamics at the elbow during rapid aiming movements for a representative participant, plotted as a function of test conditions: (DM) downward movements with gravity, (UM) upward movements against gravity; and temporal constraints: 300 ms at the *left*, 400 ms at the *middle*, 500 ms at the *right*. (a) Angular displacement; (b) Angular velocity; (c) Angular acceleration and NJM = net joint moment; (d) GDM = gravity-dependent moment; (e) GMM = generalized-muscle moment; (f) MDM = motion-dependent moment. Positive values indicate elbow extension, while negative values indicate elbow flexion.

generally accelerated the limb to a target. Yet, gravitational assist in DM resulted in less extensor muscle activities, even some flexor muscle activities for appropriate limb acceleration (see Figures 4.2e and 4.3e). Regardless of limb extensor or flexor muscles, the significance of the manipulation in this experiment was the amount of total active muscle force output for initial impulse, which was considered as a primary determinant of the movement variability.

The analysis could hardly distinguish motion-dependent effects on limb movements (i.e., MDM) between DM and UM because of nearly identical limb kinematics (see Figures 4.2f and 4.3f). Temporal constraints of the movements (i.e., 300, 400, and 500 ms) had an impact on both limb kinematics and dynamics. The faster movements, the greater GMM for quicker acceleration, and the greater MDM in compensation.

Performance outcomes

MT and RMSE data are shown in Figure 4.4. The MT ANOVA only revealed a significant temporal constraint main effect, $F(2, 8) = 3630.44$, $p < .001$, indicating no MT differences between test conditions (i.e., DM and UM).

The analysis of RMSE yielded no interaction, but significant main effects of both test condition and temporal constraint, $F(1, 4) = 9.43$, $p < .038$, $F(2, 8) = 19.61$, $p < .002$, respectively. Consistent with a number of previous findings (e.g., Fitts, 1954; Kim et al., 1999; Meyer et al., 1988; Schmidt et al., 1979; Woodworth, 1899), RMSE increased with temporal constraints of the movements (or the average velocity of the movements), indicating speed-accuracy trade-offs. More importantly, UM resulted in larger RMSE than DM. Because of no significant MT differences or nearly identical limb kinematics between test conditions, the larger RMSE by UM was

attributable to an increase in the level of active muscle force output. The findings clearly demonstrated inherent errors in rapid aiming movements.

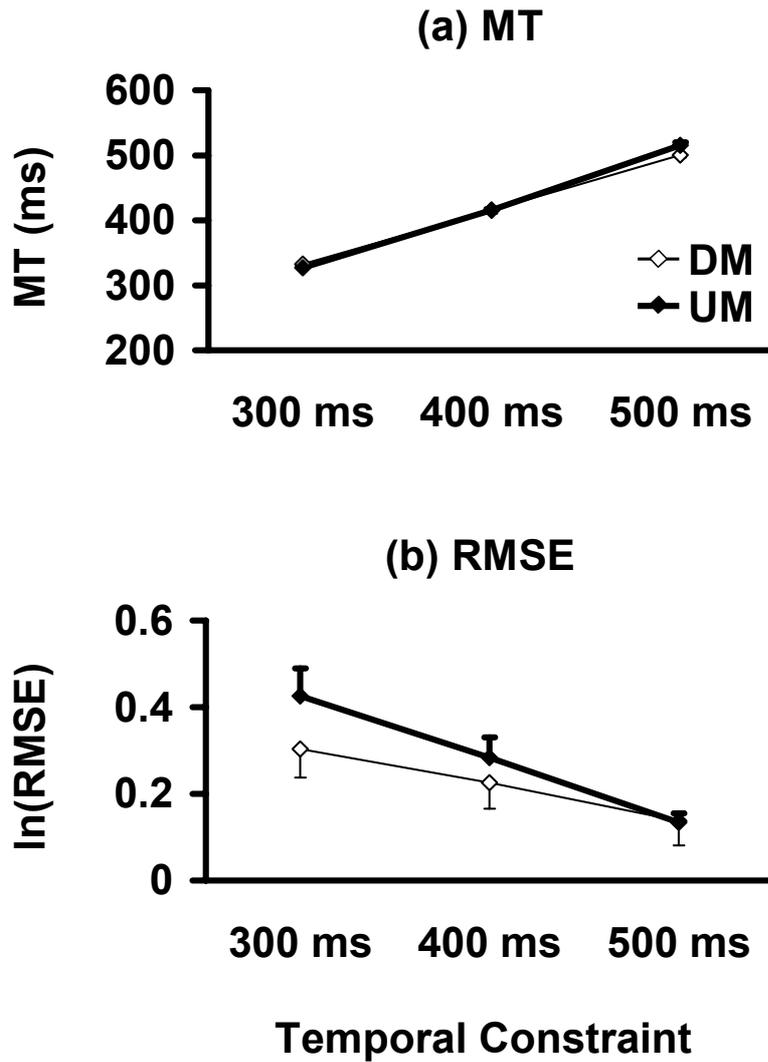


Figure 4.4. Mean performance outcome measures and standard errors as a function of test conditions: (DM) downward movements with gravity, (UM) upward movements against gravity; and temporal constraints: 300, 400, 500 ms. (a) Movement time; (b) Root mean squared error (after logarithmic transformation).

Paired-*t* tests, however, revealed that the significant RMSE difference was only for faster movements (i.e., movements with 300-ms time constraint) ($p < .022$). Perhaps, movements with 400-ms and 500-ms time constraint could afford the time for feedback-based error corrections. In particular, 500 ms was sufficient for the completion of the necessary feedback processing (e.g., Keele & Posner, 1968), resulting in no difference in RMSE. Indeed, further analyses on movement trajectories indicated that some of the 400-ms and 500-ms time-constraint movements contained error corrections, whereas most of the 300-ms time constraint-movements contained no error corrections.¹

This experiment examined spatial accuracy of rapid aiming movements by differentiating limb dynamics while keeping limb kinematics constant. The findings clearly demonstrated that variable errors in participants' movement endpoint increased with temporal constraints of the movements (or the average velocity of the movements) as well as the level of active muscle force output. Beyond kinematical analyses (e.g., Meyer et al., 1988; Schmidt et al., 1979), the current results with dynamical analyses provide further evidence supporting inherent errors in rapid aiming movements.

¹ The analyses were based on the method developed by Meyer et al. (1988). A possible initiation of an error correction phase was identified as the occurrence of one of the following movement modifications: (a) a positive-to-negative zero-line crossing in velocity, (b) a negative-to-positive zero-line crossing in acceleration trace, or (c) a significant deviation in the acceleration trace, that was, a relative minimum in the absolute value of the acceleration while the acceleration was negative.

CHAPTER V

EXPERIMENT 2: CONTROL STRATEGIES

In many daily activities, individuals execute rapid movements to specific locations in space with ease. However, some movements are difficult or nearly impossible to perform with the eyes closed because of errors inherent in the movements. In general, visual information, serving both a feedback and feedforward function, ensures optimal aiming performance (e.g., Ghez, Gordon, Ghilardi & Sainburg, 1995; Woodworth, 1899). Thus, learning at goal-directed movements involves an optimal use of vision by adapting control strategies (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003).

Typically, a performer with vision tends to increase the velocity of the primary submovement to bring the limb to the vicinity of the target quickly. Although faster movements lead to greater variability in movement endpoints, this strategy grants more time available for visual feedback utilization in the corrective submovements. As a consequence, the performer becomes increasingly proficient at central planning and controlling highly practiced movements as the construction of sensorimotor representations within the central nervous system (Ivens & Marteniuk, 1997; Proteau et al., 1987). By contrast, a performer without vision generally produces a slower, but less variable primary submovement to abandon visually-guided error corrections.

Although a considerable amount of research has been conducted on the mechanisms underlying goal-directed movements, only limited attempts have been made to quantify the mechanical causes of movements. In multi-joint aiming task,

neural-processing transforms visuospatial information about the initial hand position and the target location into motor commands to specify muscle forces and joint motions that move the hand to the desired location (Desmurget et al., 1998). This perceptual-motor transformation needs to take the dynamic properties of the moving arm into consideration because the net moment around one joint is represented as the sum of the generalized-muscle, gravity-dependent, and motion-dependent moments. Nevertheless, how visual feedback is used in controlling the intersegmental dynamics and the ways that this input may change as a function of practice are still not fully understood.

Thus, the purpose of this experiment was to examine the effects of practice and vision on the intersegmental dynamics of rapid aiming movements. As in literature, the accommodations to the motion-dependent effects were expected with practice (e.g., Heise & Cornwell, 1997; Schneider et al., 1989). However, proprioceptive feedback has been shown critical for developing internal models of the intersegmental dynamics (e.g., Gordon et al., 1995; Sainburg et al., 1999; Sainburg et al., 1995), and therefore vision might have only a slight impact on these accommodations. Nevertheless, different control strategies would emerge through the intersegmental dynamics depending on the abilities to use on-line visual feedback (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003).

Method

Participants

Twenty university students (6 females and 14 males) with no neuromuscular disorders or functional limitations in their left arms (self-declared non-dominant arms) participated in this experiment. All participants had normal or corrected-to-normal

vision and signed an institutionally approved informed consent prior to testing. The experimental protocol was approved by the University of Florida Institutional Review Board.

Task, apparatus, and procedure

The task was a 90-cm rapid aiming movement involving motions at the shoulder, elbow, and wrist joints in the horizontal plane. While sitting behind a table, participants lifted a stylus from a home position, moved their left arm in a backhand motion, and struck the stylus on a target (3 cm in diameter and 90 cm distance away) as quickly and accurately as possible (see Figure 4.1c for the overhead view of the experimental setup).

Vision was modified with a pair of occlusion goggles (PLATO SYSTEM, Translucent Technologies). The lenses on these goggles were either transparent allowing vision or translucent occluding vision without affecting the quantity of light reaching the eyes. Participants were randomly assigned to one of two vision groups. The full-vision (FV) group practiced the task with vision (a transparent state of the lenses) throughout each trial. The no-vision (NV) group, on the other hand, practiced the task without vision (a translucent state of the lenses). In the NV condition, vision was denied as soon as the stylus left the home position and became available as soon as the stylus touched on or near the target. Thus, in both vision conditions, participants received visual information before the movements and terminal feedback about the spatial endpoint of their movements.

At the beginning of each trial, participants started with the stylus at the home position. Participants then initiated their movement at any time after a tone was presented without regard to minimizing reaction time. All participants performed 560 acquisition trials (28 blocks of 20 trials) under their assigned vision condition. During

the acquisition trials, participants were given knowledge of results concerning the flight time of the stylus from the home position to the target.

Electromagnetic sensors were attached to the participants' left arm (moving arm) to represent the locations of the shoulder, elbow, wrist, and metacarpophalangeal (MP) joints (see Figure 4.1c; note that attached were electromagnetic sensors instead of reflective markers). The motion of these sensors was captured with an electromagnetic-based motion analysis system (6D-Research, Skill Technologies Inc.) operating at 60 Hz for X and Y coordinates. Coordinate data were then filtered using a low-pass, zero-lag, Butterworth digital filter with a cut-off frequency of 6.0 Hz, and used to determine the two-dimensional limb kinematics and dynamics in the primary plane of motion (i.e., the horizontal plane). Limb movements were not mechanically constrained in two-dimensions, however, only the horizontal movements were analyzed given the small number of out-of-plane deviations.

Data reduction: Intersegmental dynamics

The method of data reduction was the same as in Experiment 1, except for gravity-dependent moment (GDM) that was not included in the dynamical model for this experiment because the movements occurred primarily in the horizontal plane. The average segmental parameters for participants were: (a) upper arm (mass = 1.8 ± 0.3 kg; CM from proximal joint = 16.2 ± 1.2 cm; moment of inertia = $1.0 \pm 0.3 \times 10^{-2}$ kg·m²); (b) forearm (mass = 1.1 ± 0.2 kg; CM from proximal joint = 10.8 ± 1.0 cm; moment of inertia = $8.2 \pm 2.7 \times 10^{-3}$ kg·m²); (c) hand (mass = 0.5 ± 0.1 kg; CM from proximal joint = 8.4 ± 0.7 cm; moment of inertia = $5.9 \pm 1.8 \times 10^{-4}$ kg·m²).

Data analyses: Dependent measures

For each trial, average net joint moment (NJM), generalized-muscle moment (GMM), and motion-dependent moment (MDM) in the acceleration and deceleration

phases were calculated. The acceleration phase was defined as the period from movement onset until the moment changed its direction (i.e., from positive to negative or vice versa), whereas the deceleration phase was the period from the end of the acceleration phase until participants hit the target (see Figure 3.2 for an exemplar time series). Average moments (in Nm) were then normalized to body mass (in kg) and acromion-styilion length (in m), resulting in a unit of N/kg.

In addition, movement time (MT) and root mean square error (RMSE) of aiming accuracy were computed to evaluate overall performance. MT was defined as the flight time of the stylus from the home position to the target, whereas aiming accuracy was defined as radial distance between the edge of the target and the point of contact of the stylus. Because the accuracy distributions were not normal, the RMSE scores were transformed to $\ln(\text{RMSE})$ by taking the natural log of the data.

The RMSE and MT data were analyzed using a 2 (Vision: FV and NV) \times 28 (Trial Block) analysis of variance (ANOVA) with repeated measures on the second factor. For average NJM, GMM, and MDM, 28 blocks of 20 trials were first divided into 4 phases of 7 blocks. Then, the first (early practice level) and last (late practice level) blocks of each phase were contrasted with a 2 (Vision) \times 4 (Acquisition Phase) \times 2 (Practice Level: Early and Late) ANOVA with repeated measures on the last two factors. All statistical tests were conducted with alpha set at .05. When appropriate, Greenhouse-Geisser conservative degrees of freedom adjustments were reported.

Results and Discussion

Performance outcomes

MT and RMSE data are shown in Figure 5.1. The MT ANOVA revealed a significant Vision \times Trial Block interaction, $F(27, 486) = 1.91, p < .005$. Further, a

trial block main effect was significant, $F(27, 486) = 15.66, p < .001$, indicating that both vision groups decreased their MT as a function of practice. A vision main effect was not yet significant.

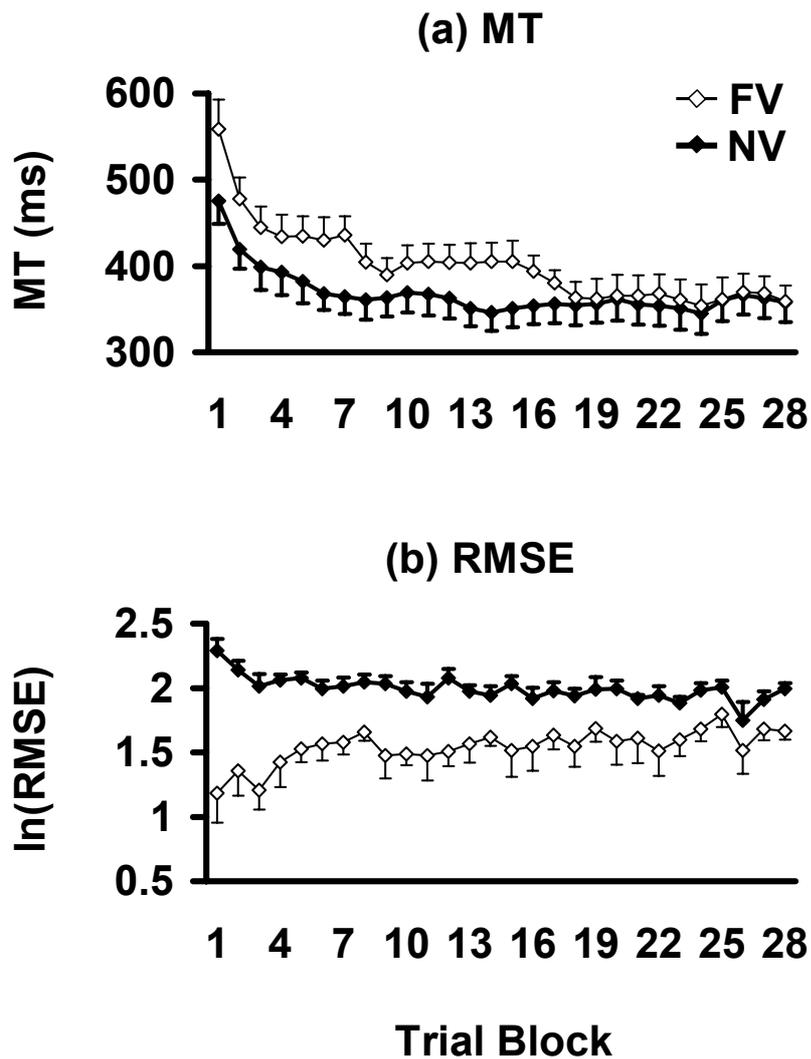


Figure 5.1. Mean performance outcome measures and standard errors as a function of trial block and vision: (FV) full-vision group, (NV) no-vision group. (a) Movement time; (b) Root mean squared error (after logarithmic transformation).

The analysis of RMSE also yielded a significant Vision \times Trial Block interaction, $F(27, 486) = 2.14, p < .001$. Further, a vision main effect was significant, $F(1, 18) = 20.86, p < .001$, indicating that movements performed with vision were more accurate than without vision. The interaction resulted from speed-accuracy trade-offs by the FV group early in practice in relation to the improved performance by the NV group, and might conceal a trial block main effect.

The performance outcome results clearly demonstrated that regardless of with or without vision, participants improved their performance by minimizing MT without sacrificing RMSE. Vision yet ensured more accurate performance throughout practice.

Limb kinematics and dynamics

Figures 5.2 and 5.3 present an exemplar time series of limb kinematics and dynamics at the shoulder and elbow, respectively, during rapid aiming movements for representative FV and NV participants. An analysis of intersegmental dynamics revealed that with practice, participants exploited the passive-interactive properties of the moving system (i.e., MDM), together with the mechanical properties of the muscle (i.e., GMM), to properly accelerate the limb to a target (i.e., NJM) (e.g., Heise & Cornwell, 1997; Schneider et al., 1989).

Average NJM, GMM, and MDM (after normalized to body mass and acromion-styloid length) in the acceleration and deceleration phases at the shoulder and elbow are illustrated in Figures 5.4 and 5.5, respectively, as respect to all participants. The ANOVAs yielded significant trial block and practice level main effects on all aspects of the intersegmental dynamics, $F_s(3, 54) > 10.00, p < .01$, and $F_s(1, 18) > 8.00, p < .02$, respectively. Essentially, all moment components increased in magnitude with practice (e.g., Heise & Cornwell, 1997; Schneider et al., 1989).

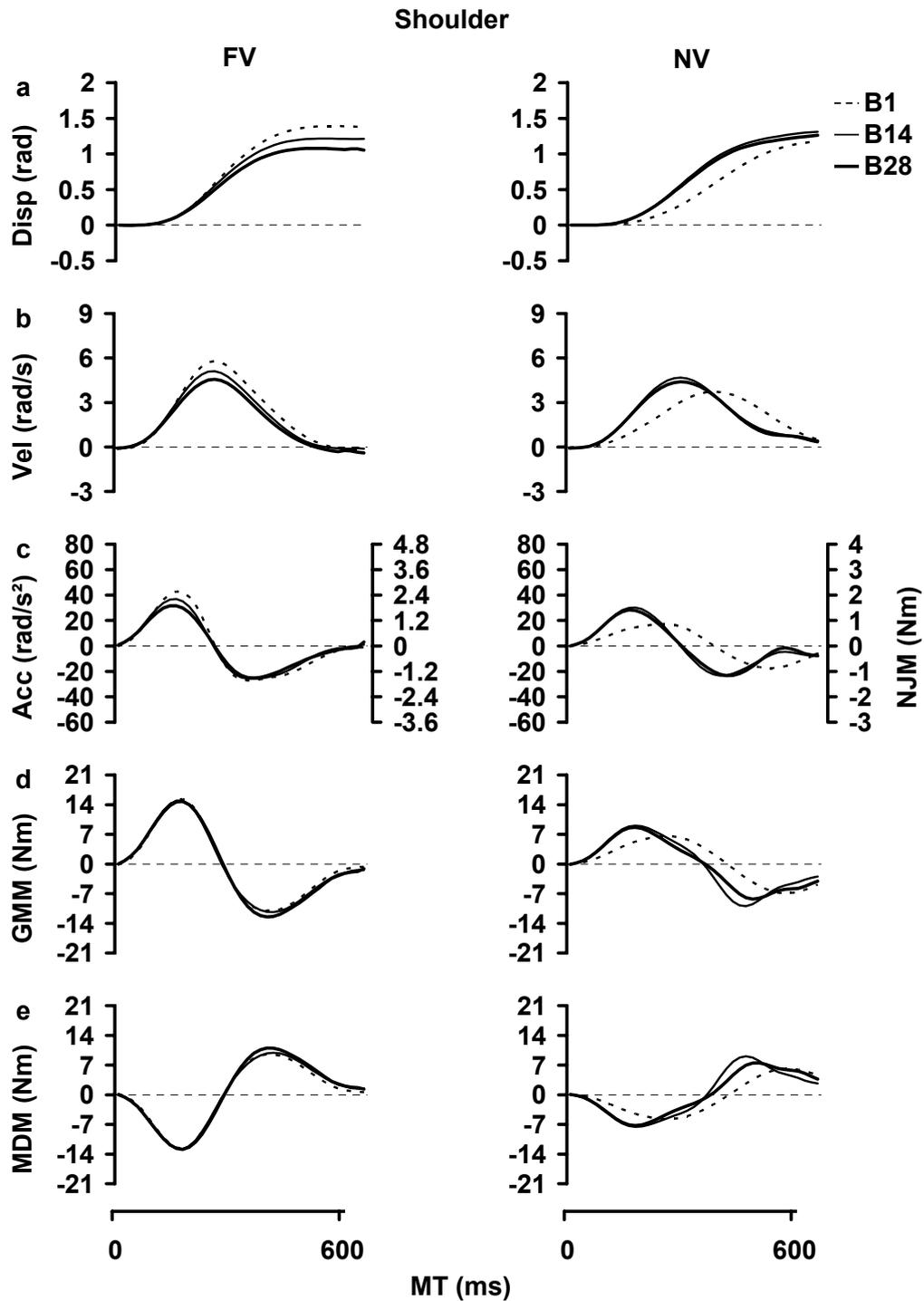


Figure 5.2. An exemplar time series of limb kinematics and dynamics at the shoulder during rapid aiming movements for a representative (FV) full-vision and (NV) no-vision participants at the *left* and *right*, respectively, plotted as a function of trial block: (B1) trial block 1, (B14) trial block 14, (B28) trial block 28. (a) Angular displacement; (b) Angular velocity; (c) Angular acceleration and NJM = net joint moment; (d) GMM = generalized-muscle moment; (e) MDM = motion-dependent moment. Positive values indicate shoulder horizontal abduction, while negative values indicate shoulder horizontal adduction.

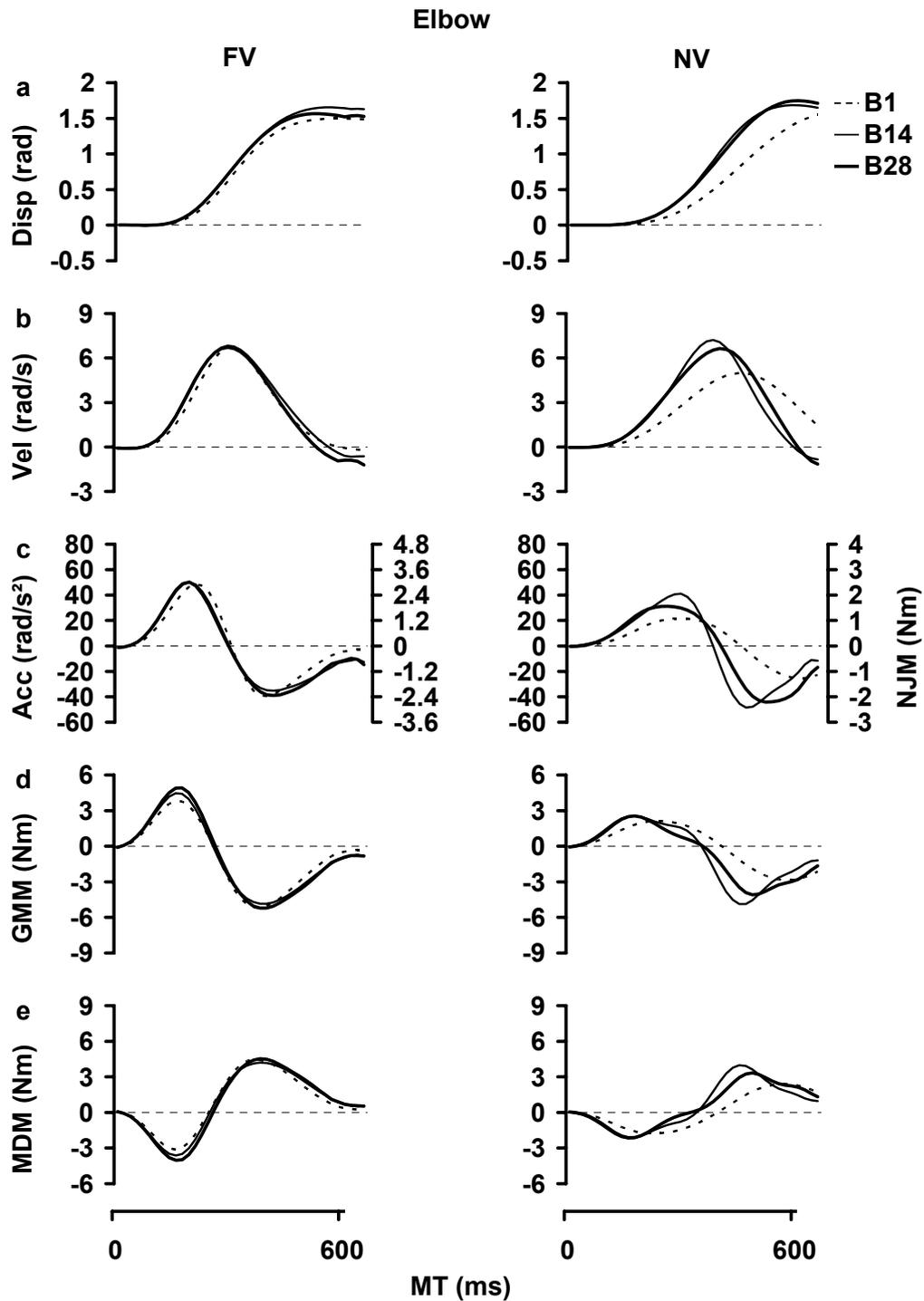


Figure 5.3. An exemplar time series of limb kinematics and dynamics at the elbow during rapid aiming movements for a representative (FV) full-vision and (NV) no-vision participants at the *left* and *right*, respectively, plotted as a function of trial block: (B1) trial block 1, (B14) trial block 14, (B28) trial block 28. (a) Angular displacement; (b) Angular velocity; (c) Angular acceleration and NJM = net joint moment; (d) GMM = generalized-muscle moment; (e) MDM = motion-dependent moment. Positive values indicate elbow extension, while negative values indicate elbow flexion.

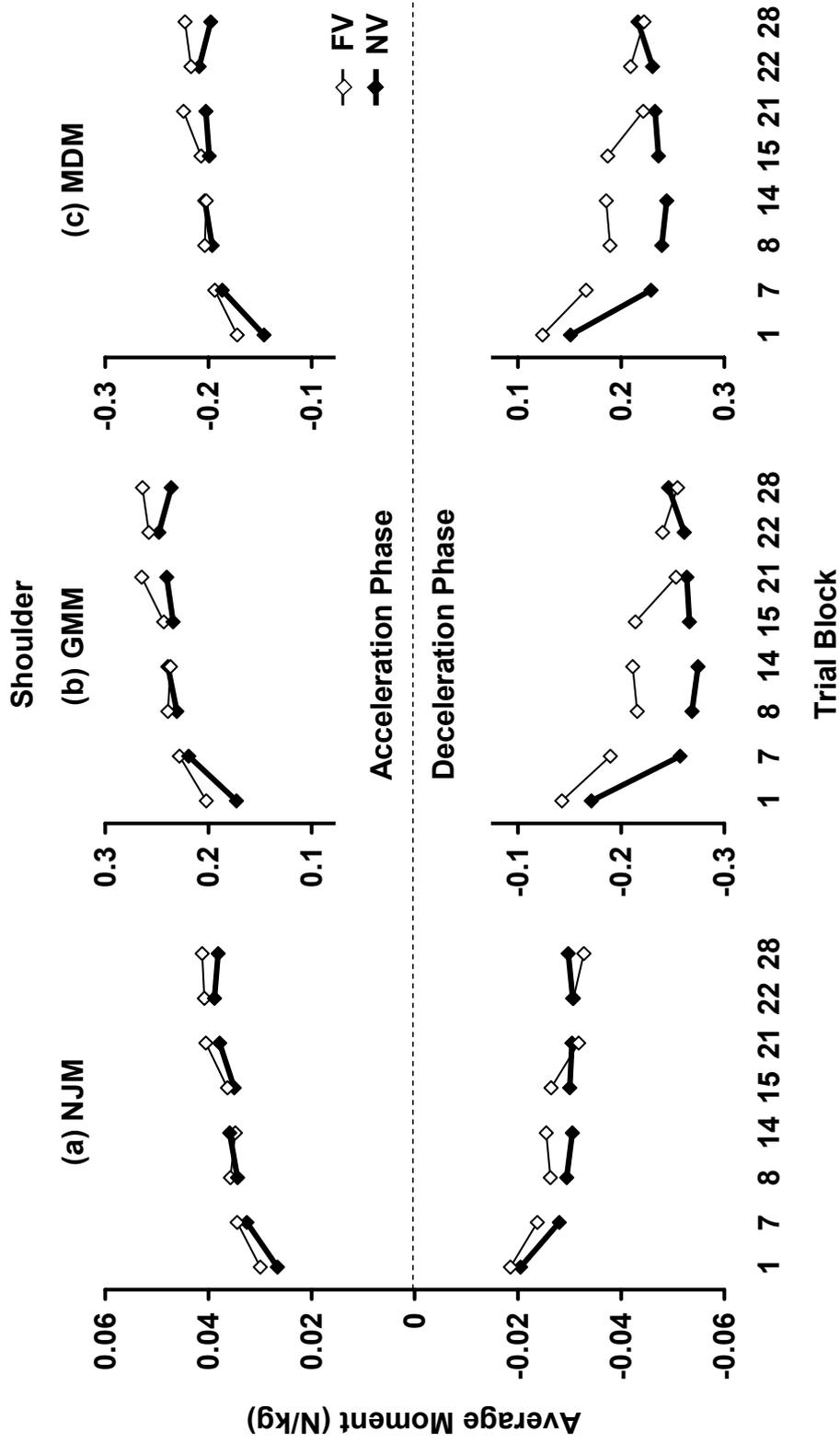


Figure 5.4. Mean average limb dynamics (after normalized to body mass and acromion-styloid length) in the acceleration and deceleration phases at the shoulder as a function of trial block and vision: (FV) full-vision group, (NV) no-vision group. (a) NJM = net joint moment; (b) GMM = generalized-muscle moment; (c) MDM = motion-dependent moment.

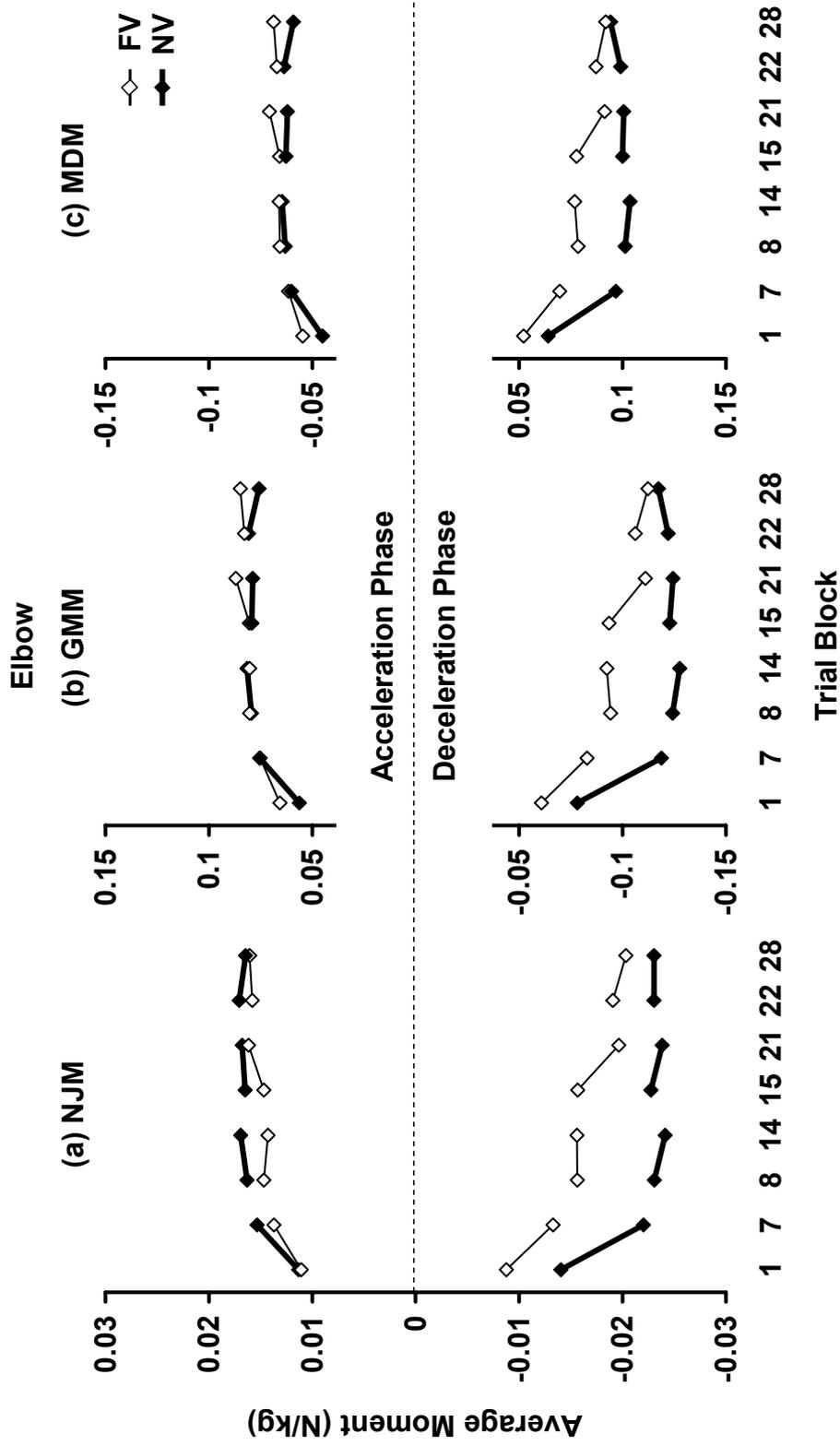


Figure 5.5. Mean average limb dynamics (after normalized to body mass and acromion-styloid length) in the acceleration and deceleration phases at the elbow as a function of trial block and vision: (FV) full-vision group, (NV) no-vision group. (a) NJM = net joint moment; (b) GMM = generalized-muscle moment; (c) MDM = motion-dependent moment.

The ANOVAs also demonstrated a significant Trial Block \times Practice Level interaction in GMM at the elbow in the acceleration phase, $F(3, 54) = 6.93, p < .04$; however, no other interactions or vision main effects were significant. The equivalent vision conditions indicated that vision had only a slight impact on the accommodations to the motion-dependent effects. Perhaps, a learned representation and/or proprioceptive feedback were more critical in developing internal models of the intersegmental dynamics (e.g., Gordon et al., 1995; Sainburg et al., 1999; Sainburg et al., 1995).

Although no statistically significant vision main effect due to the larger dispersion of the moment data, the aspects of the intersegmental dynamics was quite distinctive. Specifically, in comparison to the other vision group, the FV group produced greater average GMM in the acceleration phase; whereas, the NV group produced greater average GMM in the deceleration phase. Presumably, the FV participants favored a fast, but highly variable primary submovement to bring the limb to the vicinity of the target quickly. Despite greater variability in movement endpoints, this strategy assured more time available for visual feedback utilization in the corrective submovements. By contrast, the NV participants could not depend on visually-guided error corrections, and therefore favored a slower, but less variable primary submovement. The findings suggest different control strategies depending on the abilities to use on-line visual feedback (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003).

In this experiment, the effects of practice and vision on the intersegmental dynamics of rapid aiming movements were examined. With practice, the accommodations to the motion-dependent effects were evident. Although vision had

only a slight impact on these accommodations, different control strategies emerged through the intersegmental dynamics depending on the abilities to use on-line visual feedback.

CHAPTER VI

EXPERIMENT 3: INSTANT ADAPTATION

An essential aspect of voluntary motor function is the ability to reach for a target in space. In the preceding experiment, regardless of the levels of practice, performing rapid movements to a target with vision favored a fast, but highly variable primary submovement; whereas, without vision favored a slower, but less variable primary submovement. The findings suggest different control strategies depending on the abilities to use on-line visual feedback (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003). This subsequent experiment was designed to further investigate how humans adapt their control strategies to a new task condition even if learning was established.

A recent proposition, the specificity of practice hypothesis views learning as the construction of sensorimotor representations within the central nervous system that becomes increasingly proficient at central planning and controlling highly practiced movements (Ivens & Marteniuk, 1997). As is evident, optimal aiming performance is attributed to the availability of on-line vision, and therefore the withdrawal of vision later in practice results in larger aiming errors (e.g., Proteau, 1992; Proteau, et al., 1987). Potentially, such a specificity of practice effect (Proteau, 1992) can be overcome through the adaptation of control strategies (e.g., Khan et al., 2002; Khan & Franks, 2000). Nevertheless, dynamical evidence is not yet available.

Hence, the aim of this experiment was to examine the effect of withdrawing vision later in practice on the intersegmental dynamics of rapid aiming movements. To avoid a deteriorating loss in aiming accuracy due to a specificity of practice effect,

participants would adapt their control strategies by instantly altering the intersegmental dynamics. Rationale behind this hypothesis was optimality in goal-directed movements through a reciprocal interplay between central planning and on-line feedback processing (e.g., Khan et al., 2002; Khan & Franks, 2000).

Method

Participants, task, and apparatus

Participants, task, and apparatus were the same as in Experiment 2. Again, participants were required to perform a 90-cm rapid aiming movement as quickly and accurately as possible.

Procedure

Following Experiment 2 (i.e., after 560 acquisition trials), both full-vision (FV) and no-vision (NV) participants completed a transfer test that consisted of 20 trials under the NV condition without either spatial or temporal knowledge of results. A 5-min break was provided between Experiments 2 and 3.

Data reduction and analyses

All aspects of data reduction and analyses were identical to that used in Experiment 2, except for an experimental design. To determine a specificity of practice effect, the transfer test was compared to the preceding acquisition trial block (i.e., trial block 28). All dependent measures (performance outcomes: MT, RMSE; limb dynamics: average NJM, GMM, MDM) were submitted to a 2 (Vision: FV and NV) \times 2 (Test Condition: Acquisition and Transfer) analysis of variance (ANOVA) with repeated measures on the second factor. All statistical tests were conducted with alpha set at .05.

Results and Discussion

Performance outcomes

MT and RMSE data are shown in Figure 6.1. The MT ANOVA failed to reach a significant interaction or main effects, indicating no evidence for a specificity of practice effect.

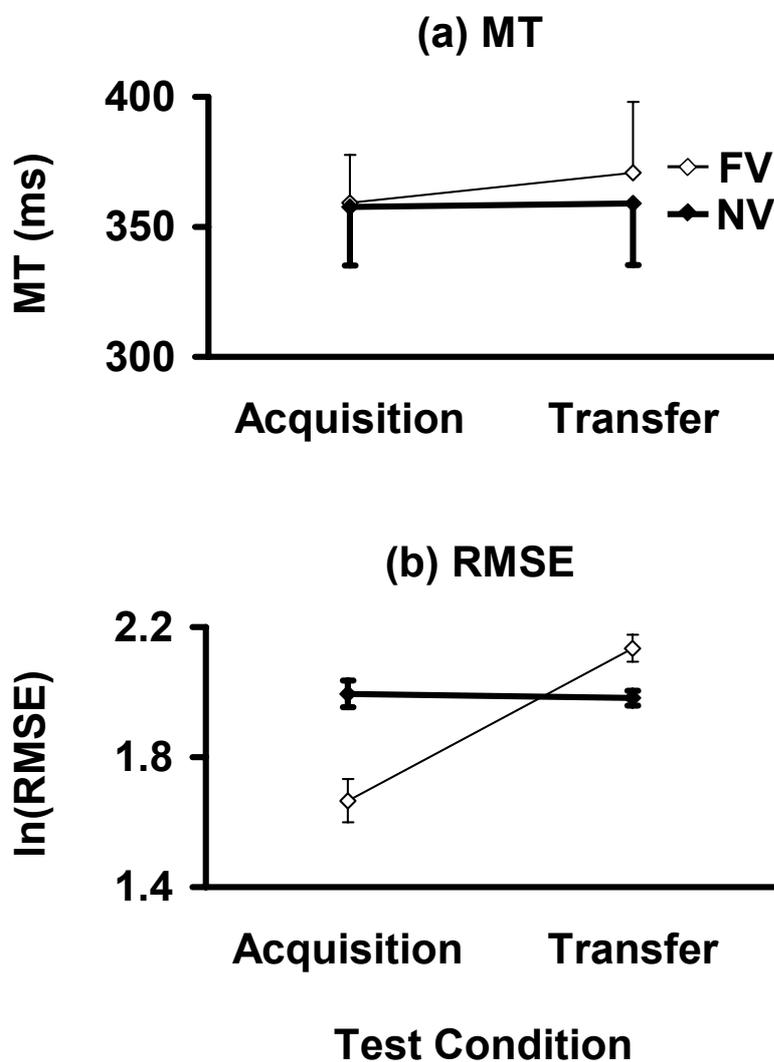


Figure 6.1. Mean performance outcome measures and standard errors as a function of test condition: acquisition, transfer; and vision: (FV) full-vision group, (NV) no-vision group. (a) Movement time; (b) Root mean squared error (after logarithmic transformation).

The analysis of RMSE yielded a significant Vision \times Test Condition interaction, $F(1, 18) = 37.62, p < .001$. This interaction was attributed to a larger acquisition-to-transfer decrement by the FV group in relation to the constant performance of the NV group. Further, a test condition main effect was significant, $F(1, 18) = 33.44, p < .001$; whereas the vision main effect was not. Consistent with previous work (e.g., Proteau, 1992; Proteau, et al., 1987), the withdrawal of vision later in practice caused an increase in RMSE, indicating a specificity of practice effect.

Limb kinematics and dynamics

Figures 6.2 and 6.3 present an exemplar time series of limb kinematics and dynamics at the shoulder and elbow, respectively, during rapid aiming movements for representative FV and NV participants (the same participants as in Figures 5.2 and 5.3). With respect to all participants, average NJM, GMM, and MDM (after normalized to body mass and acromion-styilion length) in the acceleration and deceleration phases at the shoulder and elbow are illustrated in Figures 6.4 and 6.5, respectively.

The ANOVAs only yielded significant Vision \times Test Condition interactions in NJM, MDM and GMM at the shoulder in the acceleration phase, $F_s(1, 18) = 4.45, 4.75$ and 5.01 , respectively, $p < .05$. These interactions resulted from a decrease in the magnitudes of moments by the FV group, while a slight increase by the NV group. The findings suggest a specificity of practice effect on the intersegmental dynamics at the shoulder in the acceleration phase. No other interactions or main effects were significant at the elbow or in the deceleration phase.

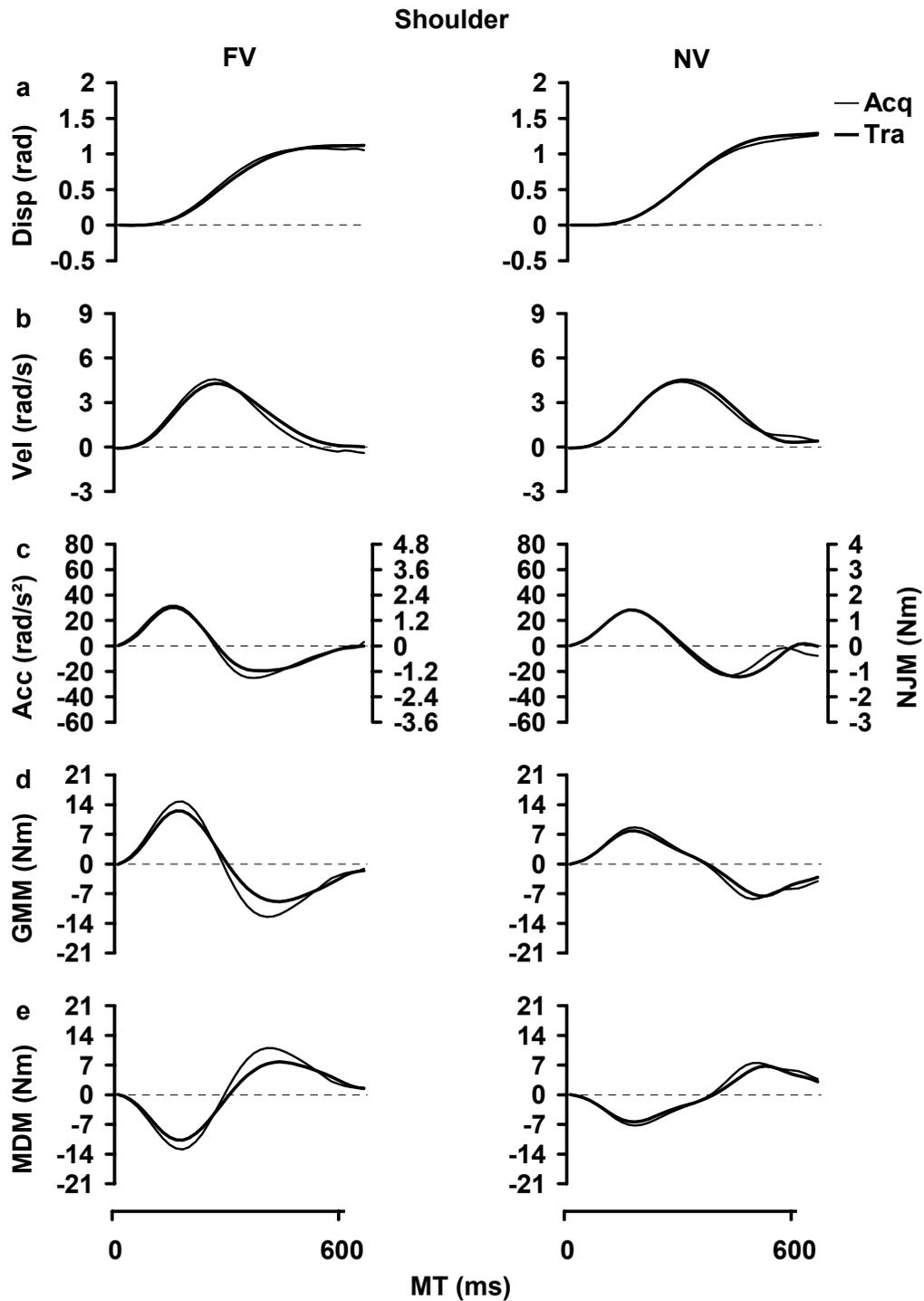


Figure 6.2. An exemplar time series of limb kinematics and dynamics at the shoulder during rapid aiming movements for a representative (FV) full-vision and (NV) no-vision participants at the *left* and *right*, respectively, plotted as a function of test condition: (Acq) acquisition, (Tra) transfer. (a) Angular displacement; (b) Angular velocity; (c) Angular acceleration and NJM = net joint moment; (d) GMM = generalized-muscle moment; (e) MDM = motion-dependent moment. Positive values indicate shoulder horizontal abduction, while negative values indicate shoulder horizontal adduction.

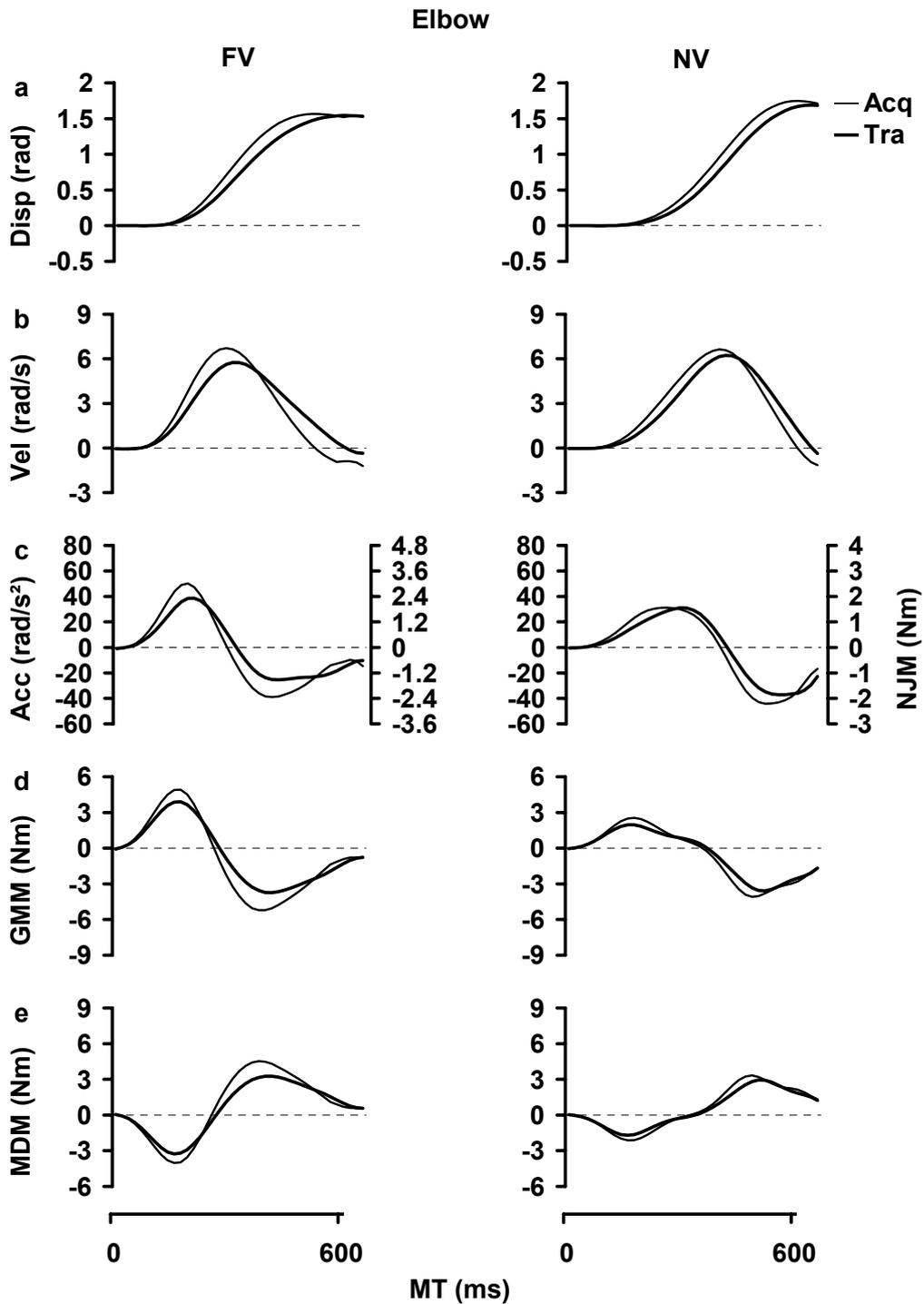


Figure 6.3. An exemplar time series of limb kinematics and dynamics at the elbow during rapid aiming movements for a representative (FV) full-vision and (NV) no-vision participants at the *left* and *right*, respectively, plotted as a function of test condition: (Acq) acquisition, (Tra) transfer. (a) Angular displacement; (b) Angular velocity; (c) Angular acceleration and NJM = net joint moment; (d) GMM = generalized-muscle moment; (e) MDM = motion-dependent moment. Positive values indicate elbow extension, while negative values indicate elbow flexion.

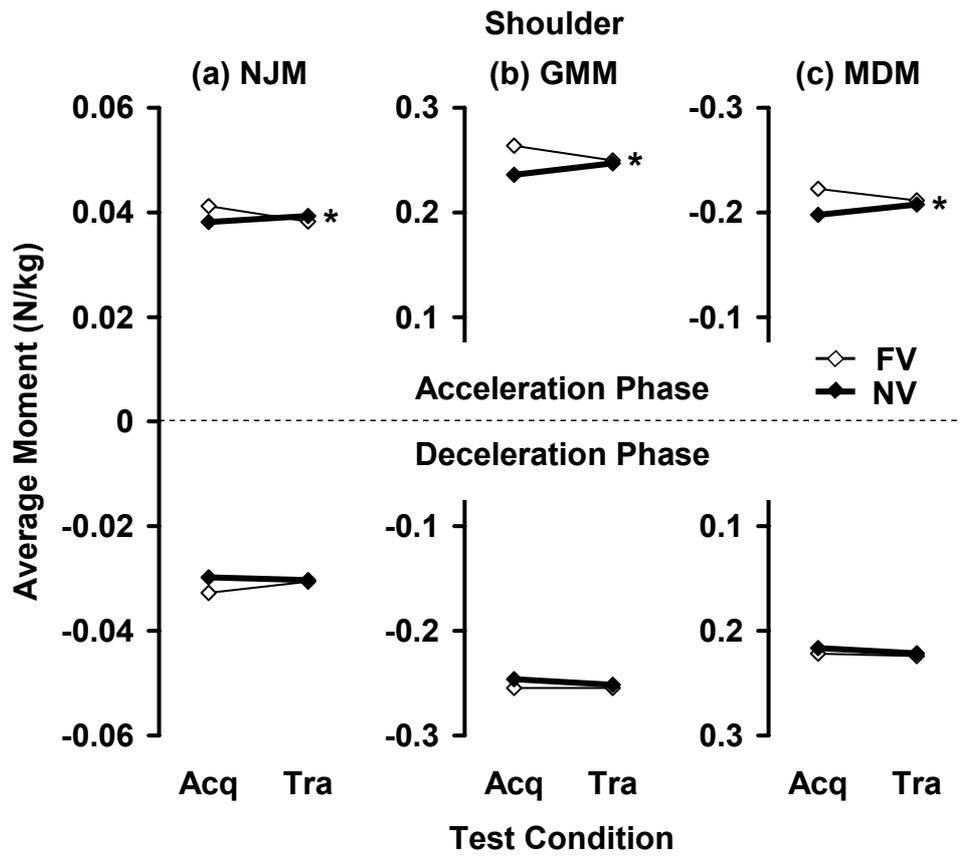


Figure 6.4. Mean average limb dynamics (after normalized to body mass and acromion-stylian length) in the acceleration and deceleration phases at the shoulder as a function of test condition: (Acq) acquisition, (Tra) transfer; and vision: (FV) full-vision group, (NV) no-vision group. (a) NJM = net joint moment; (b) GMM = generalized-muscle moment; (c) MDM = motion-dependent moment. * = a significant interaction.

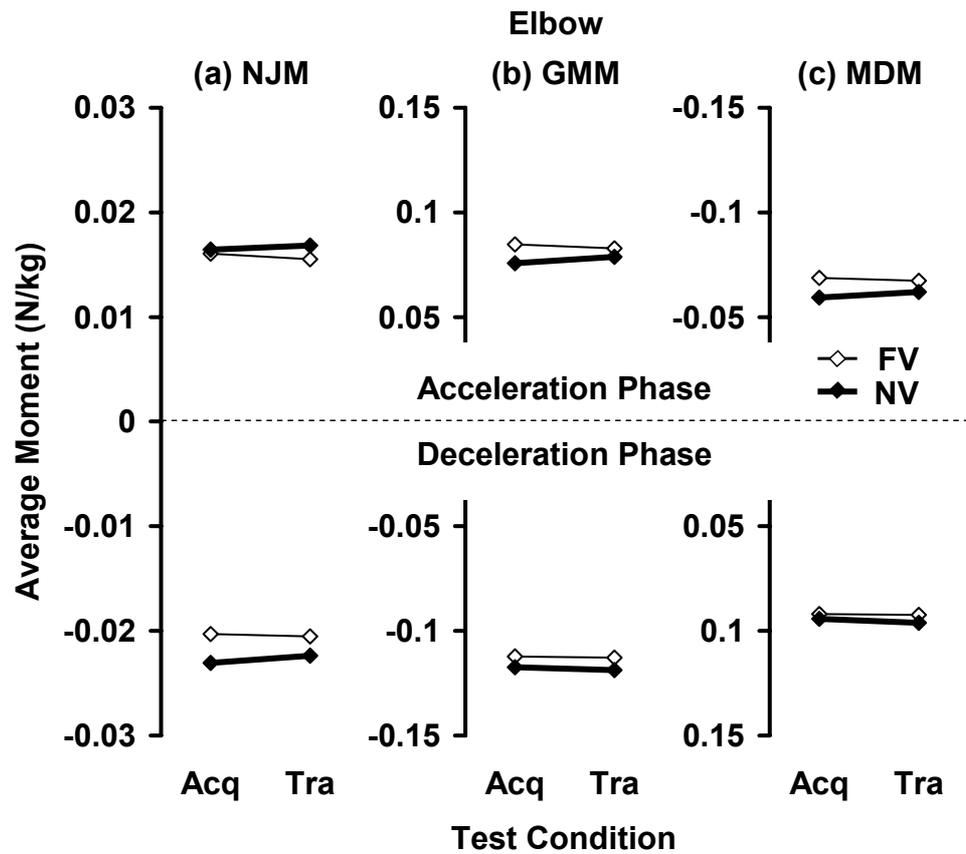


Figure 6.5. Mean average limb dynamics (after normalized to body mass and acromion-styloid length) in the acceleration and deceleration phases at the elbow as a function of test condition: (Acq) acquisition, (Tra) transfer; and vision: (FV) full-vision group, (NV) no-vision group. (a) NJM = net joint moment; (b) GMM = generalized-muscle moment; (c) MDM = motion-dependent moment.

The specificity of practice effect on the intersegmental dynamics clearly demonstrated that the FV participants adapted their control strategies to avoid a deteriorating loss in aiming accuracy. Specifically, in the transfer test, the FV participants reduced the magnitudes of moments. Apparently, the FV participants now favored a slower, but less variable primary submovement to abandon visually-guided error corrections (e.g., Khan et al., 2002; Khan & Franks, 2000). In other words, the FV participants did not accelerate their movements the same as when vision was available during acquisition. This instant adaptation of control strategies to the withdrawal of vision could reflect the flexibility of the human motor control system to compensate during rapid aiming movements through a reciprocal interplay between central planning and on-line feedback processing (e.g., Khan et al., 2002; Khan & Franks, 2000).

This experiment examined the effect of withdrawing vision on the intersegmental dynamics of rapid aiming movements. To avoid a deteriorating loss in aiming accuracy, participants adapted their control strategies by instantly altering the intersegmental dynamics, suggesting the flexibility of the human motor control system to compensate during rapid aiming movements through a reciprocal interplay between central planning and on-line feedback processing (e.g., Khan et al., 2002; Khan & Franks, 2000).

CHAPTER VII GENERAL DISCUSSION

This study was designed to provide further evidence on how goal-directed movements were controlled and what were the mechanisms responsible for the relationship between movement speed and accuracy. In particular, three experiments were conducted dealing with the intersegmental dynamics of rapid aiming movements. On the basis of the findings from Experiments 1, 2 and 3, the present chapter discusses optimality in rapid aiming movements, in detail regarding inherent errors, control strategies, and instant adaptation.

Inherent Errors

In Experiment 1, spatial accuracy of rapid aiming movements was examined by differentiating limb dynamics while keeping limb kinematics constant. An analysis of the intersegmental dynamics indicated that movements with gravity required greater active muscle forces in the acceleration phase; whereas movements against gravity required greater active muscle forces in the deceleration phase. Although nearly identical limb kinematics (i.e., angular displacement, velocity, and acceleration), variable errors in participants' movement endpoint were significantly greater for the movements against gravity than with gravity. The findings clearly demonstrate that the amount of movement variability increases as the level of force output increases, consistent with the existing models of goal-directed movements (e.g., Meyer et al., 1988; Schmidt et al., 1979). Specifically, greater force led to greater variability in force and thus greater variability in movements.

As lengthening movement time, however, differences in errors in the movement endpoints diminished regardless of the level of active muscle force output. Finally, movement time of 500 ms resulted in no differences in errors, suggesting feedback-based error corrections (e.g., Keele & Posner, 1968). Indication is straightforward; errors are inherent in the primary submovements that increase as a function of the level of active muscle force output. Furthermore, visual feedback is critical in ensuring optimal aiming performance.

Control Strategies

Experiment 2 examined the effects of practice and vision on the intersegmental dynamics of rapid aiming movements. An analysis of intersegmental dynamics demonstrated that with practice, participants exploited the passive-interactive properties of the moving system, together with the mechanical properties of the muscle, to properly accelerate the limb to a target (e.g., Heise & Cornwell, 1997; Schneider et al., 1989). The equivalent vision conditions, however, indicated that vision had only a slight impact on these accommodations. Perhaps, a learned representation and/or proprioceptive feedback were more critical in developing internal models of the intersegmental dynamics (e.g., Gordon et al., 1995; Sainburg et al., 1999; Sainburg et al., 1995).

During practice, participants improved their performance by minimizing movement time without sacrificing aiming accuracy. However, performing with vision was superior to without vision because of more accurate performance, indicating that vision was important for optimal aiming. Presumably, optimal performance was achieved by producing a fast, but highly variable primary submovement to bring the limb to the vicinity of the target quickly. The advantage of

this strategy was to assure more time available for visual feedback utilization in the corrective submovements. Indeed, participants with vision appeared to generate stronger muscle forces in the acceleration phase. By contrast, participants without vision could not depend on visually-guided error corrections, and therefore generated weaker muscle forces in the acceleration phase for a slower, but less variable primary submovement. The findings clearly suggest different control strategies depending on the abilities to use on-line visual feedback (e.g., Elliott et al., 1995; Khan et al., 2002; Khan & Franks, 2000, 2003).

Instant Adaptation

Following Experiment 2, the effect of withdrawing vision later in practice on the intersegmental dynamics of rapid aiming movements was determined in Experiment 3. In the transfer test, the withdrawal of vision resulted in a decrease in the magnitudes of moments, suggesting a specificity of practice effect. An important implication is that participants instantly adapted their control strategies to avoid a deteriorating loss in aiming accuracy. Apparently, participants with vision in practice now favored a slower, but less variable primary submovement to abandon visually-guided error corrections. Consistent with this interpretation is the fact that the removal of vision resulted in an increase in time spent for the primary submovements (Khan et al., 2002; Khan & Franks, 2000). Such instant adaptation of control strategies to the withdrawal of vision could reflect the flexibility of the human motor control system to compensate during rapid aiming movements through a reciprocal interplay between central planning and on-line feedback processing (e.g., Khan et al., 2002; Khan & Franks, 2000).

An alternative interpretation of the transfer result is that withdrawing vision produced a constriction of the perceived movement space (i.e., distance between the home position and the target).² During practice, participants executed a fast, but highly variable primary submovement, apparently relying on on-line visual feedback for optimal aiming performance. However, in the transfer test, neither the participants' arm nor the location of the target was visible at movement initiation. In the context, slower acceleration may reflect alternation to control strategies that involved remembering the environment/perceived workspace (e.g., Lemay & Proteau, 2002).

Another possible explanation is that participants altered their control strategies in transfer because visual information provided by the ongoing stylus was impossible. In rapid aiming tasks, individuals typically look at the target and thus the stylus is only visible in the far periphery of the retina before movement initiation. Because visual information of the ongoing stylus was significant for movement control (e.g., Proteau & Cournoyer, 1990), participants might adapt their control strategies bringing the stylus into central vision as quickly as possible during practice. However, when vision of the ongoing stylus was withdrawn, quick acceleration was no longer needed, resulting in less acceleration.

Finally, the effect of withdrawing vision on control strategies may be related to task constraints. On-line vision was shown less useful in ensuring optimal performance when aiming at a smaller target (Proteau & Isabelle, 2002), variable practice schedule (Tremblay et al, 2002), uncertainty of vision availability (Khan et al., 2002), or vision use constraint (Elliott et al., 1998). If so, the withdrawal of vision

² The appreciation is extended to Dr. Luc Proteau for suggesting this alternative interpretation.

would be less detrimental to control strategies. Resolution of such an issue will help clarify how goal-directed movements are optimized.

Limitation and Future Direction

The current findings should be interpreted cautiously because of the method of intersegmental dynamics. Although net joint moment (NJM), motion-dependent moment (MDM), and gravity-dependent moment (GDM) are directly calculated from the limb kinematics, generalized-muscle moment (GMM) is a residual term. Besides active muscle forces, however, GMM also includes other soft tissue forces crossing the joint. Furthermore, movements depended on the net muscle moment, and therefore GMM does not necessarily reflect the agonist-antagonist coactivation.

The mechanical properties of the moving arm are another concern. Muscle fibers shorten at specific speeds while concurrently developing force to rotate a limb segment (i.e., the force-velocity relationships). In addition, the amount of force produced by a muscle is related to the length at which the muscle is held (i.e., the force-length relationship). Furthermore, not all of the force produced by the muscle is put to use in generating rotation of the limb segment, but depending on the angle at which the joint is held (i.e., the torque-angle relationship). Visco-elastic behavior of the tendon should be taken into consideration as well because the mechanical interaction between the tendon and the muscle depends on the amount of force being applied or generated, the speed of the muscle action, and the slack in the tendon (Proske & Morgan, 1987). The use of electromyography and ultrasonography may help assess more accurate activities and behaviors of the muscle and tendon.

Conclusions

Of particular interest in this study was how humans adapted their control strategies in ensuring optimal performance. In an attempt to provide further evidence on the issue, rapid aiming movements were extensively investigated using the method of the intersegmental dynamics. The results clearly demonstrate that errors are inherent in the primary submovements that increase as a function of the level of active muscle force output, causing speed-accuracy trade-offs. To ensure optimal performance, however, different control strategies are possible depending on the abilities to use on-line visual feedback. More importantly, humans can instantly adapt their control strategies to avoid a deteriorating loss in performance. Such instant adaptation of control strategies is interpreted as the flexibility of the human motor control system to compensate during rapid aiming movements through a reciprocal interplay between central planning and on-line feedback processing.

APPENDIX A
INTERSEGMENTAL DYNAMICS

Net joint moment (NJM), motion-dependent moment (MDM), and gravity-dependent moment (GDM) were calculated from the coordinate data following procedures presented by Schneider et al. (1989). Generalized-muscle moment (GMM) was a residual term because the sum of GMM, MDM and GDM equaled NJM. The equation of motion for the elbow was as follows:

$$\begin{aligned}
 \text{NJM} &= (I_f + m_f r_f^2) \ddot{\phi}_f \\
 \text{MDM} &= -[K_4 \cos(\phi_f - \phi_u) + K_5 \cos(\phi_f - \phi_u) + K_1 \cos(\phi_h - \phi_u)] \ddot{\phi}_u & (\text{UAA}) \\
 &\quad -[K_4 \sin(\phi_f - \phi_u) + K_5 \sin(\phi_f - \phi_u) + K_1 \sin(\phi_h - \phi_u)] \dot{\phi}_u^2 & (\text{UAV}) \\
 &\quad -[K_6 + K_2 \cos(\phi_h - \phi_f)] \ddot{\phi}_f & (\text{FAA}) \\
 &\quad -[K_2 \sin(\phi_h - \phi_f)] \dot{\phi}_f^2 & (\text{FAV}) \\
 &\quad -[I_h + m_h r_h^2 + K_2 \cos(\phi_h - \phi_f)] \ddot{\phi}_h & (\text{HAA}) \\
 &\quad +[K_2 \sin(\phi_h - \phi_f)] \dot{\phi}_h^2 & (\text{HAV}) \\
 \text{GDM} &= -[K_3 \sin \phi_h + K_7 \sin \phi_f] g \\
 \text{GMM} &= \text{NJM} - \text{MDM} - \text{GRM}
 \end{aligned}$$

likewise, the equation of motion for the shoulder was as follows:

$$\begin{aligned}
 \text{NJM} &= (I_u + m_u r_u^2) \ddot{\phi}_u \\
 \text{MDM} &= -[K_8 + K_9 + K_1 \cos(\phi_h - \phi_u) + (K_4 + K_5) \cos(\phi_f - \phi_u)] \ddot{\phi}_u & (\text{UAA}) \\
 &\quad -[K_1 \sin(\phi_h - \phi_u) + (K_4 + K_5) \sin(\phi_f - \phi_u)] \dot{\phi}_u^2 & (\text{UAV}) \\
 &\quad -[I_f + m_f r_f^2 + K_6 + K_2 \cos(\phi_h - \phi_f) + (K_4 + K_5) \cos(\phi_f - \phi_u)] \ddot{\phi}_f & (\text{FAA}) \\
 &\quad -[K_2 \sin(\phi_h - \phi_f) - (K_4 + K_5) \sin(\phi_f - \phi_u)] \dot{\phi}_f^2 & (\text{FAV}) \\
 &\quad +[I_h + m_h r_h^2 - K_2 \cos(\phi_h - \phi_f) - K_1 \cos(\phi_h - \phi_u)] \ddot{\phi}_h & (\text{HAA}) \\
 &\quad +[K_2 \sin(\phi_h - \phi_f) + K_1 \sin(\phi_h - \phi_u)] \dot{\phi}_h^2 & (\text{HAV}) \\
 \text{GDM} &= -[K_3 \sin \phi_h + K_7 \sin \phi_f + K_{11} \sin \phi_u] g \\
 \text{GMM} &= \text{NJM} - \text{MDM} - \text{GRM}
 \end{aligned}$$

where:

$m_h, m_f, m_u =$	masses of the hand, forearm, and upper arm
$r_h, r_f, r_u =$	distances from the proximal joint to the center of mass of each segment
$I_h, I_f, I_u =$	moments of inertia about the center of mass of each segment
$\phi_h, \phi_f, \phi_u =$	orientation angles with respect to the right horizontal for each segment (see Figure 4.1 for convention)
$l_h, l_f, l_u =$	lengths of each segment
$g =$	gravitational constant ($= 9.81 \text{ ms}^{-2}$)
$K_1 =$	$m_h r_h l_h$
$K_2 =$	$m_h r_h l_f$
$K_3 =$	$m_h r_h$
$K_4 =$	$m_h l_f l_u$
$K_5 =$	$m_f r_f l_u$
$K_6 =$	$m_h l_f^2$
$K_7 =$	$m_h l_f + m_f r_f$
$K_8 =$	$m_f l_u^2$
$K_9 =$	$m_h l_u^2$
$K_{11} =$	$m_f l_u + m_h l_u + m_u r_u$
UAA =	moment due to upper arm angular acceleration
UAV =	moment due to upper arm angular velocity
FAA =	moment due to forearm angular acceleration,
FAV =	moment due to forearm angular velocity,
HAA =	moment due to hand angular acceleration
HAV =	moment due to hand angular velocity

APPENDIX B MOMENT OF INERTIA

Moment of inertia of each segment (upper arm, forearm, and hand) about the transverse axis through the center of mass was predicted from the participants' anthropometric data using regression equations presented by Hinrichs (1985). The equations for each segment were:

$$\text{Upper arm: } I_u = 10.268 (ACRDL) + 5.0655 (ELBOC) - 349.71$$

$$\text{Forearm: } I_f = 9.5544 (WRISC) + 10.452 (RDSTL) - 371.11$$

$$\text{Hand: } I_h = 2.7443 (HANDB) - 16.882$$

where:

<i>ACRDL</i> =	acromion-radiale length
<i>ELBOC</i> =	elbow circumference
<i>WRISC</i> =	wrist circumference
<i>RDSTL</i> =	radiale-stylian length
<i>HANDB</i> =	hand circumference.

* Moments of inertia in $\text{kg}\cdot\text{cm}^2$ and anthropometric data in cm.

APPENDIX C
INFORMED CONSENT

**Motor Behavior Laboratory
University of Florida**

Informed Consent

Protocol Title: Specificity of Practice and Intersegmental Dynamics in Rapid Aiming Limb Movements

Principal Investigator: Masashi Yoshida, BS, Master's Student, Department of Exercise and Sport Sciences, (352) 374-9972, myoshida@ufl.edu

Supervisor: James H. Cauraugh, Ph.D., Associate Professor, Department of Exercise and Sport Sciences, FLG 132-F, (352) 392-0584 ext. 1273, jcaura@hhp.ufl.edu

Purpose of the research study:

The purpose of this study is to investigate aiming movements to a target. Depending on your group assignment, your movements will be executed either with or without vision of the target.

What you will be asked to do in the study:

Prior to participation, anthropometric measurements of your left arm will be taken (e.g., length, circumference, and breadth). Then, you will begin performing the rapid aiming movement task (a 90-cm movement to a 3-cm target). You will hold a stylus in your left hand as you move as quickly and accurately as possible from the home position to the target. You will perform 600 movement trials under your assigned vision condition (vision or no vision). On each trial, your aiming accuracy as well as movement time will be recorded automatically.

Time required:

The experiment will take approximately 2 hours.

Risks and Benefits:

This study is minimal risk. The risks of harm anticipated are not greater than that ordinarily encountered in your daily life or through routine physical or psychological examinations. Regular rest periods will be provided during testing. There is no expected benefit from your participation in this study.

Compensation:

No monetary compensation will be given for participation.

Confidentiality:

Your identity will be kept confidential to the extent provided by law. At the beginning of your participation, your information will be assigned a code number. The list connecting your name to this number will be locked in a filing cabinet in the Motor Behavior Laboratory. When the study is completed and the data has been analyzed, the list will be destroyed. Only group means will be reported in any publication.

Voluntary participation:

Your participation in this study is completely voluntary.

Right to withdraw from the study:

You have the right to withdraw from the study at anytime without consequence.

Whom to contact if you have questions about the study:

Masashi Yoshida, BS, Master's Student, Department of Exercise and Sport Sciences, (352) 374-9972, myoshida@ufl.edu

James H. Cauraugh, Ph.D., Associate Professor, Department of Exercise and Sport Sciences, FLG 132-F, (352) 392-0584 ext. 1273, jcaura@hhp.ufl.edu

Whom to contact about your rights as a research participant in the study:

UFIRB Office, Box 112250, University of Florida, Gainesville, FL, 32611-2250; ph 392-0433

Agreement:

I have read the procedure described above. I voluntarily agree to participate in this study, and I will be given a copy of this consent if I request one.

Participant's Signature: _____ Date: _____

Principal Investigator's Signature: _____ Date: _____

研究に関する説明と参加の同意書

研究課題：Optimal Control Strategies in Rapid Aiming Movements

研究責任者：吉田雅司，早稲田大学大学院 人間科学研究科 博士後期課程 2 年，
連絡先：電話: 042-949-8113 内線 3468，Email: myoshida@fuji.waseda.jp

指導教官：鈴木秀次，早稲田大学 人間科学部 教授
連絡先：電話: 042-949-8113 内線 6308，Email: shujiwhs@waseda.jp

研究目的：本研究の目的は，Rapid Aiming Movements の遂行過程に対し，実験心理学，バイオメカニクス，神経生理学的な分析を加え，その制御・学習メカニズムを多角的に検証し，身体運動の最適化に必要な要素を明らかにするものです。

研究概要：

実験で行う内容：あなたがこの実験で行う内容は Rapid Aiming Movements です。Rapid Aiming Movements とは，手に持ったペンをスタート地点から出来るだけ早く，あるいは決められた時間内（300-600 ms）で，より正確にターゲットまで移動させる動作です。あなたにはこの動作を，椅子に座った状態又はベッドに横たわった状態で行っていただきます。

測定する項目：

- (1) 移動にかかった時間，及びその正確性を測定します。
- (2) 動作中の腕の動きを測定します。測定に際して肩，肘，手首，中指付根に光が反射するマーカー又は磁気センサーを取り付けます。身体に対して磁気の影響はありません。
- (3) 動作中の筋肉の活動を測定します。測定に際して肩，腕に電極を貼り付けます。身体に流れる極めて微弱な電流を感知するのみで，電流が逆流する心配はありません。

実験に要する時間：実験に要する時間は約 1 時間です。

予期される危険性：この実験への参加又は動作を行うことによって予期される精神的・身体的な危険性はありません。

プライバシーの保護：この研究はヘルシンキ宣言及び早稲田大学人間科学部「人を対象とした研究」倫理指針に遵守して行われており，あなたのプライバシーは保護されています。すべてのデータ・ファイルはナンバー化し保存され，いかなる場合においてもあなたの名前は公表されません。

任意による参加と被験者の権利：実験への参加は任意です。またあなたはいかなる場合においても，無条件で実験への参加を取り止める権利を有しています。

プライバシーに関する問合せ先：早稲田大学人間科学部研究倫理委員会，早稲田大学所沢キャンパス人間科学部事務所内

実験参加の同意確認：私は上記の内容を熟読し理解した上で，この実験に参加することを承諾します。

被験者署名： _____ 年 月 日

研究責任者署名： _____ 年 月 日

RELATED ARTICLES

- Yoshida, M., Cauraugh, J. H., & Chow, J. W. (2003). Effects of vision and practice on intersegmental dynamics of rapid aiming movements [Abstract]. *Proceedings of the International Society of Biomechanics XIXth Congress, Dunedin, New Zealand*, 433.
- Yoshida, M., Cauraugh, J. H., & Chow, J. W. (2004). Specificity of practice, visual information, and intersegmental dynamics in rapid-aiming limb movements. *Journal of Motor Behavior*, 36, 281-290.
- Yoshida, M., & Suzuki, S. (2004). Generalized muscle moment and spatial inconsistency in rapid aiming movements [Abstract]. *Journal of Sport & Exercise Psychology*, 26, S204.

REFERENCES

- Abrams, R. A., & Pratt, J. (1993). Rapid aimed limb movements: Differential effects of practice on component submovements. *Journal of Motor Behavior, 25*, 288-198.
- Bard, C., Hay, L., & Fleury, M. (1985). Role of peripheral vision in the directional control of rapid aiming movements. *Canadian Journal of Psychology, 39*, 151-161.
- Bastian, A. J., Martin, T. A., Keating, J. G., & Thach, W. T. (1996). Cerebellar ataxia: abnormal control of interaction torques across multiple joints. *Journal of Neurophysiology, 76*, 492-509.
- Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.
- Brebner, J. (1968). Continuing and reversing the direction of responding movements: Some exceptions to the so-called "psychological refractory period." *Journal of Experimental Psychology, 78*, 120-127.
- Carlton, L. G. (1979). Control processes in the production of discrete aiming responses. *Journal of Human Movement Studies, 5*, 115-124.
- Carlton, L. G. (1981a). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 1019-1030.
- Carlton, L. G. (1981b). Visual information: The control of aiming movements. *Quarterly Journal of Experimental Psychology, 33A*, 87-93.
- Carlton, L. G. (1992). Visual processing time and the control of movement. In L. Proteau & D. Elliott (Eds.), *Vision and motor control* (pp. 3-31). Amsterdam: North-Holland.
- Carson, R. G., Chua, R., Elliott, D., & Goodman, D. (1990). The contribution of vision to asymmetries in manual aiming. *Neuropsychologia, 28*, 1215-1220.
- Carson, R. G., Goodman, D., Chua, R., & Elliott, D. (1993). Asymmetries in the regulation of visually guided aiming. *Journal of Motor Behavior, 25*, 21-32.
- Chua, R., & Elliott, D. (1993). Visual regulation of manual aiming. *Human Movement Science, 12*, 365-401.

- Clauser, C. E., McConville, J. T., & Young, J. W. (1969). Weight, volume and center of mass of segments of the human body. *AMRL Technical Report*, 69-70. Wright-Patterson Air Force Base, OH.
- Crossman, E. R. F. W., & Goodeve, P. J. (1963/1983). Feedback control of hand-movements and Fitts' law. Paper presented at the meeting of the Experimental Psychology Society, Oxford, July 1963. Published in the *Quarterly Journal of Experimental Psychology*, 35A, 251-278.
- Beggs, W. D. A., & Howarth, C. I. (1970). Movement control in a repetitive motor task. *Nature*, 221, 752-753.
- Beggs, W. D. A., & Howarth, C. I. (1972). The accuracy of aiming at a target: Some further evidence for a theory of intermittent control. *Acta Psychologica*, 36, 171-177.
- Desmurget, M., Epstein, C. M., Turner, R. S., Prablanc, C., Alexander, G. E., & Grafton, S. T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience*, 2, 563-567.
- Desmurget, M., Pelisson, D., Rossetti, Y., & Prablanc, C. (1998). From eye to hand: Planning goal-directed movements. *Neuroscience and Biobehavioral Reviews*, 22, 761-788.
- Elliott, D., Binsted, G., & Heath, M. (1999). The control of goal-directed limb movements: Correcting errors in the trajectory. *Human Movement Science*, 18, 121-136.
- Elliott, D., Carson, R. G., Goodman, D., & Chua, R. (1991). Discrete vs. continuous visual control of manual aiming. *Human Movement Science*, 10, 393-418.
- Elliott, D., Chua, R., Pollock, B. J., & Lyons, J. (1995). Optimizing the use of vision in manual aiming: The role of practice. *Quarterly Journal of Experimental Psychology*, 48A, 72-83.
- Elliott, D., Helsen, W. F., & Chua, R. (2001). Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin*, 127, 342-357.
- Elliott, D., & Jaeger, M. (1988). Practice and the visual control of manual aiming movements. *Journal of Human Movement Studies*, 14, 279-291.
- Elliott, D., Lyons, J., & Dyson, K. (1997). Rescaling an acquired discrete aiming movement: Specific or general motor learning? *Human Movement Science*, 16, 81-96.
- Elliott, D., Ricker, K. L., & Lyons, J. (1998). The control of sequential goal-directed movement: Learning to use feedback or central planning? *Motor Control*, 2, 61-80.

- Enoka, R. M. (2002). *Neuromechanics of human movement* (3rd ed.). Champaign, IL: Human Kinetics.
- Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, *47*, 381-391.
- Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology*, *67*, 103-112.
- Ghez, C., Gordon, J., & Ghilardi, M. F. (1995). Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy. *Journal of Neurophysiology*, *73*, 361-372.
- Ghez, C., Gordon, J., Ghilardi, M. F., & Sainburg, R. (1995). Contributions of vision and proprioception to accuracy in limb movements. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 549-564). Cambridge, MA: MIT Press.
- Gordon, J., Ghilardi, M. F., & Ghez, C. (1995). Impairments of reaching movements in patients without proprioception. I. Spatial errors. *Journal of Neurophysiology*, *73*, 347-360.
- Gribble, P. L., & Ostry, D. J. (1999). Compensation for interaction torques during single- and multijoint limb movement. *Journal of Neurophysiology*, *82*, 2310-2326.
- Guiard, Y. (1993). On Fitts's and Hooke's laws: Simple harmonic movement in upper-limb cyclical aiming. *Acta Psychologica*, *82*, 139-159.
- Heath, M., Hodges, N. J., Chua, R., & Elliott, D. (1998). On-line control of rapid aiming movements: Effects of target characteristics on manual aiming. *Canadian Journal of Experimental Psychology*, *52*, 163-173.
- Heise, G. D., & Cornwell, A. (1997). Relative contributions to the net joint moment for a planar multijoint throwing skill: Early and late in practice. *Research Quarterly for Exercise and Sport*, *68*, 116-124.
- Hinrichs, R. N. (1985). Regression equations to predict segmental moments of inertia from anthropometric measurements: An extension of the data of Chandler et al. (1975). *Journal of Biomechanics*, *18*, 621-624.
- Hirashima, M., Kudo, K., & Ohtsuki, T. (2003). Utilization and compensation of interaction torques during ball-throwing movements. *Journal of Neurophysiology*, *89*, 1784-96.
- Hirata, C., & Yoshida, S. (2000). Visual dominance in amending the directional parameter of feedforward control. *Journal of Motor Behavior*, *32*, 17-25.

- Hollerbach, J. M., & Flash, T. (1982). Dynamic interactions between limb segments during planar arm movement. *Biological Cybernetics*, 44, 67-77.
- Hoy, M. G., & Zernicke, R. F. (1986). The role of intersegmental dynamics during rapid limb oscillations. *Journal of Biomechanics*, 19, 867-877.
- Ivens, C. J., & Marteniuk, R. G. (1997). Increased sensitivity to changes in visual feedback with practice. *Journal of Motor Behavior*, 29, 326-338.
- Jagacinski, R. J., Repperger, D. W., Moran, M. S., Ward, S. L., & Glass, B. (1980). Fitts' law and the microstructure of rapid discrete movements. *Journal of Experimental Psychology: Human Perception and Performance*, 6, 309-320.
- Keele, S.W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, 70, 387-403.
- Keele, S.W., & Posner, M. I. (1968). Processing of visual feedback in rapid movements. *Journal of Experimental Psychology*, 77, 155-158.
- Khan, M. A., Elliott, D., Coull, J., Chua, R., & Lyons, J. (2002). Optimal control strategies under different feedback schedules: Kinematic evidence. *Journal of Motor Behavior*, 34, 45-57.
- Khan, M. A., & Franks, I. M. (2000). The effect of practice on component submovements is dependent on the availability of visual feedback. *Journal of Motor Behavior*, 32, 227-240.
- Khan, M. A., & Franks, I. M. (2003). Online versus offline processing of visual feedback in the production of component submovements. *Journal of Motor Behavior*, 35, 285-295.
- Khan, M. A., Franks, I. M., & Goodman, D. (1998). The effect of practice on the control of rapid aiming movements: Evidence for an interdependency between programming and feedback processing. *Quarterly Journal of Experimental Psychology*, 51A, 425-444.
- Kim, S., Carlton, L. G., Liu, Y. T., & Newell, K. M. (1999). Impulse and movement space-time variability. *Journal of Motor Behavior*, 31, 341-357.
- Krakauer, J. W., Ghilardi, M. F., & Ghez, C. (1999). Independent learning of internal models for kinematic and dynamic control of reaching. *Nature Neuroscience*, 2, 1026-1031.
- Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 8, 113-128.

- Lashley, K. S. (1917). The accuracy of movement in the absence of excitation from the moving organ. *American Journal of Physiology*, *43*, 169-194.
- Lemay, M., & Proteau, L. (2002). Effects of target presentation time, recall delay, and aging on the accuracy of manual pointing to remembered targets. *Journal of Motor Behavior*, *34*, 11-23.
- MacKenzie, C. L., Marteniuk, R. G., Dugas, C., Liske, D., & Eickmeier, B. (1987). Three-dimensional movement trajectories in Fitts' task: Implications for control. *Quarterly Journal of Experimental Psychology*, *39A*, 629-647.
- Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, *95*, 340-370.
- Meyer, D. E., Smith, J. E. K., Kornblum, S., Abrams, R. A., & Wright, C. E. (1990). Speed-accuracy tradeoffs in aimed movements: Toward a theory of rapid voluntary action. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 173-226). Hillsdale, NJ: Erlbaum.
- Meyer, D. E., Smith, J. E. K., & Wright, C. E. (1982). Models for the speed and accuracy of aimed movements. *Psychological Review*, *89*, 449-482.
- Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford, England: Oxford University press.
- Newell, K. M., & Carlton, L. G., (1985). On the relationship between peak force and peak force variability in isometric tasks. *Journal of Motor Behavior*, *17*, 230-241.
- Newell, K. M., Carlton, L. G., Kim, S., & Chung, C. H. (1993). The accuracy of movement in space-time. *Journal of Motor Behavior*, *25*, 23-44.
- Pew, R. W. (1966). Acquisition of hierarchical control over the temporal organization of a skill. *Journal of Experimental Psychology*, *71*, 764-771.
- Phillips, S. J., Roberts, E. M., & Huang, T. C. (1983). Quantification of intersegmental reactions during rapid swing motion. *Journal of Biomechanics*, *16*, 411-418.
- Plamondon, R., (1995a). A kinematic theory of rapid human movements: Part I. Movement representation and generation. *Biological Cybernetics*, *72*, 295-307.
- Plamondon, R., (1995b). A kinematic theory of rapid human movements: Part II. Movement time and control. *Biological Cybernetics*, *72*, 309-320.

- Plamondon, R., & Alimi, A. M. (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral and Brain Sciences*, *20*, 279-349.
- Pratt, J., & Abrams, R. A. (1996). Practice and component submovements: The roles of programming and feedback in rapid aimed movements. *Journal of Motor Behavior*, *28*, 149-156.
- Proske, U., & Morgan, D. L. (1987). Tendon stiffness: Methods of measurement and significance for the control of movement. A review. *Journal of Biomechanics*, *20*, 75-82.
- Proteau, L. (1992). On the specificity of leaning and the role of visual information for movement control. In L. Proteau & D. Elliott (Eds.), *Vision and motor control* (pp. 67-103). Amsterdam: North-Holland.
- Proteau, L., & Cournoyer, J. (1990). Vision of the stylus in a manual aiming task: The effects of practice. *Quarterly Journal of Experimental Psychology*, *42A*, 811-828.
- Proteau, L., & Isabelle, G. (2002). On the role of visual afferent information for the control of aiming movements toward targets of different sizes. *Journal of Motor Behavior*, *34*, 367-384.
- Proteau, L., Marteniuk, R. G., Girouard, Y., & Dugas, C. (1987). On the type of information used to control and learn an aiming movement after moderate and extensive training. *Human Movement Science*, *6*, 181-199.
- Proteau, L., Marteniuk, R. G., & Lévesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *Quarterly Journal of Experimental Psychology*, *44A*, 557-575.
- Putnam, C. A. (1991). A segment interaction analysis of proximal-to-distal sequential segment motion patterns. *Medicine and Science in Sports and Exercise*, *23*, 130-144.
- Sainburg, R. L., Ghez, C., & Kalakanis, D. (1999). Intersegmental dynamics are controlled by sequential anticipatory, error correction, and postural mechanisms. *Journal of Neurophysiology*, *81*, 1045-1056.
- Sainburg, R. L., Ghilardi, M. F., Poizner, H., & Ghez, C. (1995). The control of limb dynamics in normal subjects and patients without proprioception. *Journal of Neurophysiology*, *73*, 820-835.
- Sanes, J. N., & Jennings, V. A. (1984). Centrally programmed patterns of muscle activity in voluntary motor behavior of humans. *Experimental Brain Research*, *54*, 23-32.

- Schmidt, R. A., & McCabe, J. F. (1976). Motor program utilization over extended practice. *Journal of Human Movement Studies*, 2, 239-247.
- Schmidt, R. A., Zelaznik, H. N., & Frank, J. S. (1978). Sources of inaccuracy in rapid movement. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 183-203). New York: Academic Press.
- Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., & Quinn, J. T. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. *Psychological Review*, 86, 415-451.
- Schneider, K., Zernicke, R. F., Schmidt, R. A., & Hart, T. J. (1989). Changes in limb dynamics during the practice of rapid arm movements. *Journal of Biomechanics*, 22, 805-817.
- Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. Urbana, IL: University of Illinois Press.
- Sherwood, D. E., & Schmidt, R. A. (1980). The relationship between force and force variability in minimal and near-maximal static and dynamic contractions. *Journal of Motor Behavior*, 12, 75-89.
- Sherwood, D. E., Schmidt, R. A., & Walter, C. B. (1988). The force/force-variability relationship under controlled temporal conditions. *Journal of Motor Behavior*, 20, 106-116.
- Slifkin, A. B., & Newell, K. M. (1999). Noise, information transmission, and force variability. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 837-851.
- Smits-Engelsman, B. C. M., Van Galen, G. P., & Duysens, J. (2002). The breakdown of Fitts' law in rapid, reciprocal aiming movements. *Experimental Brain Research*, 145, 222-230.
- Soechting, J. F. (1984). Effect of target size on spatial and temporal characteristics of a pointing movement. *Experimental Brain Research*, 54, 121-132.
- Stroeve, S. (1997). A learning feedback and feedforward neuromuscular control model for two degrees of freedom human arm movements. *Human Movement Science*, 16, 621-651.
- Stroeve, S. (1998). Neuromuscular control model of the arm including feedback and feedforward components. *Acta Psychologica*, 100, 117-131.
- Tremblay, L., & Proteau, L. (1998). Specificity of practice: The case of powerlifting. *Research Quarterly for Exercise and Sport*, 69, 284-289.

- Tremblay, L., Welsh, T. N., & Elliott, D. (2001). Specificity versus variability: Effects of practice conditions on the use of afferent information for manual aiming. *Motor Control, 5*, 347-360.
- Vince, M. A., (1948). Corrective movements in a pursuit task. *Quarterly Journal of Experimental Psychology, 1*, 85-103.
- Wallace, S. A., & Newell, K. M. (1983). Visual control of discrete aiming movement. *Quarterly Journal of Experimental Psychology, 35A*, 311-321
- Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review, 3*, (2, Whole No. 13).
- Zelaznik, H. N., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aiming movements. *Journal of Motor Behavior, 15*, 217-236.

BIOGRAPHICAL SKETCH

Masashi Yoshida was born and raised in Japan. He graduated from the Nippon College of Physical Education, Japan, in 1991, with a Bachelor of Science in Physical Education. After several years' professional experience in strength training and conditioning, he earned his Master of Science in Exercise and Sport Sciences from the University of Florida, U.S.A., in 2001, emphasized in motor learning and control. In 2002, Masashi was admitted to the Ph.D. program in the Graduate School of Human Sciences at Waseda University, Japan.