Preparation and control of quick and fast movements: Neurophysiological and dynamical perspectives

Kazutoshi Kudo^{1*}, Masaya Hirashima² and Akito Miura^{3,4}

¹ Department of Life Sciences, Graduate School of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

² Division of Physical and Health Education, Graduate School of Education, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

³ Research Center of Health, Physical Fitness and Sports, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan

⁴ Japan Society for the Promotion of Science, 8 Ichiban-cho, Chiyoda-ku, Tokyo 102-8472, Japan

Received: January 8, 2014 / Accepted: February 4, 2014

Abstract Quickness of response and movement speed are required for achieving athletic success in a variety of sports, and are often lost in various movement disorders. Because cognitive processes such as anticipation, attention, and planning are required for preparation of a quick motor response, we first introduce recent neurophysiological studies that have revealed brain activities underlying the preparation for movement, with some neurophysiological applications to improve motor quickness. Moreover, recent developments in the dynamical analysis of complex movements allow us to understand precise mechanisms and principles underlying fast multi-joint and multi-limb movements. We introduce our current theories on the mathematical analysis of complex movement coordination called induced acceleration analysis. We propose that movements are subject to both instantaneous and cumulative effects, which combine to integrate the torque and acceleratory forces on multiple joints. We also discuss evidence that movement rate has important effects on the coordination patterns, acting as a control parameter that determines organization of movement patterns. These findings underscore the necessity of conducting research on the science of movement that is highly interdisciplinary, including the fields of physiology, biomechanics, neurosciences, and behavioral sciences not only for the enhancement of sports performance, but also for the facilitation of motor recovery and rehabilitation from neurological damage.

Keywords : human, quick and fast movements, brain activity, rhythmic motor coordination, dynamics, dynamical systems

Introduction

Among a variety of measures of motor performance, quickness of response and movement speed are often highly significant parameters for achieving athletic success¹⁾. For example, the soccer striker who can run faster than an opponent defender has the advantage of reaching a ball first to make the goal-winning shot. The strong fast-ball pitcher has an advantage over the batter because of the batter's shorter preparation time before the swing. The boxer, who can deliver punches quickly enough to land a hard blow on an opponent before the opponent is able to dodge the punch, has many more chances to knock down an opponent.

To move more quickly, one has to shorten both preparation time and execution time for the movement. Cognitive

processes such as anticipation, attention, and planning are crucial components in preparing for a quick motor response. Therefore, we first introduce recent neurophysiological studies that have revealed brain activities underlying preparation for movement.

In addition, it is not an easy job for the central nervous system to plan and control high-speed movements such as ball throwing because of the complex and dynamic properties of the human body. Multiple limb segments are linked by joints, and the angular acceleration of a given joint in a multi-joint system at a certain instant is determined not only by the joint torques and gravity torque at that instant, but also by the time series of the joint torques and gravity torque applied to the system in advance²⁾. Spatiotemporal organization of rhythmic multi-limb movements is also difficult because planned and intended movement patterns are sometimes unintentionally disrupted as movement rate increases³⁻⁵⁾. Recent developments in

*Correspondence: kudo@idaten.c.u-tokyo.ac.jp

the dynamical analysis of complex movements allow us to understand precise mechanisms and principles underlying fast multi-joint and multi-limb movements.

Therefore, in this review, we discuss how quick and fast movements are controlled and organized from dual neurophysiological and dynamical perspectives.

Neurophysiological mechanisms of motor preparation

Quickness of response can be assessed with a reaction time (RT) measurement, the time interval between presentation of an imperative stimulus and onset of electromyographic activity. In performing an RT task, a number of physiological measurements show consistent changes before presentation of the imperative stimulus, indicating the importance of preparatory processes for ensuring a quick response. The measurements include heart rate⁶⁾, pupillary diameter⁶⁾, skin conductance⁷⁾, spinal reflexes⁸⁾, and electroencephalographic (EEG) activities⁹⁾. Therefore, these findings indicate that preparation of a quick response involves distributed processes in both the somatic and autonomic nervous systems.

Findings from movement disorders. The central processes of motor preparation are well known, and clearly revealed in clinical studies of movement disorders. For example, patients with Parkinson's disease, which arises from basal ganglia dysfunction, show prolonged RT¹⁰⁾, one of the factors contributing to their bradykinesia. The basal ganglia projects to the cortex via the thalamus, with its output helping focus cortical activity to produce activation of relevant muscles and inhibition of irrelevant ones. Patients with lesions of the parietal lobe show slower RTs in response to visual stimuli due to a deficit of spatial attention¹¹⁾. One patient with focal lesions in the cerebellum and brainstem showed impairment in on-line visuomotor control, including ramp-tracking and simple RTs to visual stimuli; in contrast, there was no impairment in off-line control, such as changes in visual feedback during a pointing task, suggesting that on-line control was impaired by increased delays in the visuomotor feedback loop¹²⁾. Animal studies have also reported that dysfunction of the cerebellar dentate nucleus results in prolonged RTs in monkeys¹³⁾, which suggests an involvement of cerebello-thalamo-cortical or cerebello-reticulo-spinal pathways for quick initiation of movements.

Neuroimaging studies. Neuroimaging studies have revealed the brain structures corresponding to quick RTs¹⁴⁻¹⁶⁾. Naito et al.¹⁴⁾ found that regional cerebral blood flow (rCBF) in the anterior cingulate cortex (ACC), as measured with positron emission tomography (PET), was significantly negatively correlated with mean RTs in auditory, somatosensory, and visual RT tasks. Interestingly, the ACC is associated with the midbrain reticular intralaminar thalamic system, which modulates arousal and general

attention¹⁷⁾. In addition, the ACC has reciprocal neural connections to the primary motor area, premotor area, and supplementary motor area, which in turn have direct neural connections to the spinal cord¹⁸⁾. Therefore, the ACC plays a key role in movement initiation through its enhancement of arousal and attention. Kudo et al.¹⁵⁾, using functional magnetic resonance imaging (fMRI), compared brain activity during an RT (i.e., quick) task and during a coincident-timing (i.e., non-quick) task. An identical visual stimulus was used for both tasks, and significant activation was found in the ACC, whereas deactivation was found in the MT+ area for the RT task relative to the timing task. This result suggests top-down attentional control¹⁹⁾ or central regulation²⁰⁾ during task-specific preparation for quick movement initiation. Thobois et al.¹⁶⁾ reported that, in addition to the lateral (i.e., crossed) corticospinal tract (contralateral sensorimotor cortex) and ipsilateral cerebellum, the anterior (i.e., uncrossed) corticospinal tract (ipsilateral sensorimotor cortex) and the contralateral cerebellum are recruited when quickness of response and movement speed are required.

These studies suggest that quickness of response can be achieved through the hierarchical and coordinated activities of multiple, distributed parts of the central nervous system related to arousal, attention, planning, and execution.

Possibility of neurophysiological enhancement. With the progress being made in improving our neurophysiological understanding of motor preparation, attempts have also been made to enhance quickness of response. Pascual-Leone et al.²¹⁾ reported that transcranial magnetic stimulation (TMS), delivered over the primary motor cortex (M1), shortened simple RTs to visual, auditory, and somatosensory stimuli by approximately 30 ms, suggesting that TMS activates cortico-cortical connections transferring the motor program to M1. Repetitive TMS at 1 Hz for 10 min applied to the parietal cortex has also been reported to enhance visual spatial attention²²⁾, and thus can be considered to enhance cognitive processing relevant to stimulus identification. Transcranial direct current stimulation (tDCS) has also been used to enhance performance in RT tasks²³⁾; that is, RT was shortened by weak DCs under 0.3 mA applied between the vertex and earlobe (i.e., the non-cephalic reference). Shortening of RTs by TMS or tDCS has also been reported in patients with Parkinson's disease²⁴⁾ and chronic stroke²⁵⁾.

In addition, startling acoustic stimuli (SAS) can be used to increase subcortical activation involving the reticular formation²⁶⁻²⁸⁾, and result in the initiation of movement with RTs, sometimes below 100 ms. This SAS effect of RT shortening was also observed in patients with Parkinsonian syndromes involving progressive supranuclear palsy and multisystem atrophy²⁹⁾.

Control of fast multi-joint movements

Mechanically, fast movement is difficult to control, especially when large degrees of freedom (DOFs) are involved in controlling the movement. In single-joint movements (such as an “arm curl,” which involves only the elbow joint), the mechanical DOF is considered to be equal to one, and the effect of torque on the joint rotation is very simple. The joint rotation can be controlled only by the torque at that joint as follows:

$$\ddot{\theta} = \tau / I \quad (1)$$

where $\ddot{\theta}$ is the angular acceleration, τ is the joint torque, and I is the moment of inertia.

In multi-joint movements, however, the situation is not so simple. Angular acceleration at a certain joint is affected not only by the torque at that joint but also by torques at other joints. Furthermore, velocity-dependent torque (such as Coriolis and centrifugal torque) also induces angular acceleration. Thus, it is generally difficult to grasp how a joint rotation is caused by multiple sources. At this time, we would like to introduce an analysis framework called “induced acceleration analysis,” which will promote our understanding of the mechanical cause-and-effect relationships between torques and joint rotations. In particular, we will focus on the fact that a joint rotation is caused by two different types of mechanisms: *instantaneous* and *cumulative* effects. First, we will mathematically formulate the instantaneous and cumulative effects, concurrently providing concrete examples and effective graphics. Then, we will apply this analysis to the motions involved in pitching a baseball, and demonstrate that this analysis provides helpful insights into the kinetic mechanisms of how each joint is rotated in such complex movement.

Equations of motion for 2-DOF movements. First, let us consider a 2-DOF upper-limb movement in a vertical plane (Fig. 1). Equations of motion for the upper-arm (Eq. 2) and forearm (Eq. 3) can be written in the following manner:

$$\begin{aligned} & \ddot{\theta}_1 [I_1 + I_2 + m_2 l_1^2 + m_1 r_1^2 + m_2 r_2^2 + 2m_2 l_1 r_2 \cos \theta_2] + \\ & \ddot{\theta}_2 [I_2 + m_2 r_2^2 + m_2 l_1 r_2 \cos \theta_2] \\ & = \tau_1 + \dot{\theta}_2^2 [m_2 l_1 r_2 \sin \theta_2] + \dot{\theta}_1 \dot{\theta}_2 [2m_2 l_1 r_2 \sin \theta_2] - \\ & g[(m_2 l_1 + m_1 r_1) \cos \theta_1 + m_2 r_2 \cos(\theta_1 + \theta_2)] \end{aligned} \quad (2)$$

$$\begin{aligned} & \ddot{\theta}_1 [I_2 + m_2 r_2^2 + m_2 l_1 r_2 \cos \theta_2] + \ddot{\theta}_2 [I_2 + m_2 r_2^2] \\ & = \tau_2 - \dot{\theta}_1^2 [m_2 l_1 r_2 \sin \theta_2] - g[m_2 r_2 \cos(\theta_1 + \theta_2)] \end{aligned} \quad (3)$$

where θ_i = joint angle, I_i = moment of inertia about the center of gravity, r_i = distance to center of mass from proximal joint of the segment, l_i = length, m_i = mass, τ_i = joint torque ($i = 1$: upper arm, 2 : forearm).

Fig. 1 Two-joint system in a vertical plane.

By using some substitutions, these equations can be written in the following form:

$$I_{11} \ddot{\theta}_1 + I_{12} \ddot{\theta}_2 = \tau_1 + V_1(\theta, \dot{\theta}) + g_1(\theta) \quad (4)$$

$$I_{21} \ddot{\theta}_1 + I_{22} \ddot{\theta}_2 = \tau_2 + V_2(\theta, \dot{\theta}) + g_2(\theta) \quad (5)$$

where $\theta = (\theta_1 \ \theta_2)^T$ is the joint angle vector and $\dot{\theta} = (\dot{\theta}_1, \dot{\theta}_2)^T$ is the angular velocity vector, $V_i(\theta, \dot{\theta})$ is the angular-velocity-dependent torque, and $g_i(\theta)$ is the gravity torque. Now consider a question of how much angular acceleration ($\ddot{\theta}_1$ and $\ddot{\theta}_2$) occur if joint torques (τ_1 and τ_2) are applied at the two joints when the system is in the state of θ and $\dot{\theta}$. Since unknown variables ($\ddot{\theta}_1$ and $\ddot{\theta}_2$) are present in both equations (Eq. 4 and Eq. 5), we must solve them as simultaneous equations in the following way:

$$\begin{pmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{pmatrix} = \begin{pmatrix} I_{11} & I_{12} \\ I_{21} & I_{22} \end{pmatrix}^{-1} \left\{ \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} + \begin{pmatrix} V_1(\theta, \dot{\theta}) \\ V_2(\theta, \dot{\theta}) \end{pmatrix} + \begin{pmatrix} g_1(\theta) \\ g_2(\theta) \end{pmatrix} \right\} \quad (6)$$

The instantaneous effect in a 2-DOF system. What we call the *instantaneous effect* is the angular acceleration that is *instantaneously* produced by the joint torque. Instantaneous effects correspond to the following part of Eq. 6:

$$\begin{pmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{pmatrix}^{\text{Instantaneous}} = \begin{pmatrix} I_{11} & I_{12} \\ I_{21} & I_{22} \end{pmatrix}^{-1} \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} \quad (7)$$

Each acceleration can be written as follows:

$$\begin{aligned} \ddot{\theta}_1^{\text{Instantaneous}} &= A_{11} \tau_1 + A_{12} \tau_2 \\ \ddot{\theta}_2^{\text{Instantaneous}} &= A_{21} \tau_1 + A_{22} \tau_2 \end{aligned} \quad (8)$$

where A_{11} , A_{12} , A_{21} , and A_{22} are the elements of inverse of the system inertia matrix ($I(\theta)$).

The first important point indicated by Eq. 8 is that the angular accelerations of both joints depend on both joint torques. This indicates that, for example, a shoulder joint torque (τ_1) induces angular accelerations not only at the shoulder joint but also at the elbow joint. Fig. 2a shows the simulation result when only the shoulder flexor torque is exerted on the 2-DOF (shoulder and elbow) system in a horizontal plane. It is intuitively understandable that the shoulder flexor torque induces shoulder flexion accelera-

tion, but it should be noted that it also induces elbow extension acceleration, even though the elbow joint torque is zero.

Similarly, an elbow joint torque (τ_2) induces angular accelerations at both joints. Fig. 2b shows the simulation result when only the elbow flexor torque is exerted: the elbow flexor torque induces not only elbow flexion acceleration, but also shoulder extension acceleration. Why does joint torque accelerate not only the given joint, but also other remote joints? In fact, interaction forces between body segments occur at the same time that joint torque is exerted at a certain joint if the body segments are linked by joints. These interaction forces are the causes of angular accelerations arising at remote joints.

Since the interaction forces arise instantaneously with exertion of joint torque, angular acceleration at certain remote joints also arises at the same instant. This phenomenon, which arises from the mechanical constraints of the joint, is called “dynamic coupling.”³⁰⁾

The second important point indicated by Eq. 8 is that angular accelerations produced by joint torque depend on the system inertia matrix ($I(\theta)$), namely the posture of the system. It indicates that even though the same joint torque is exerted, angular acceleration induced by the joint torque changes depending on the system’s posture at which the joint torque is exerted. Fig. 3 shows the simulation results when shoulder flexor torque is exerted in two different postures. Shoulder flexor torque induces shoulder

Fig. 2 Simulated motions of the two-joint (shoulder and elbow) system in a horizontal plane. Fig. 2a shows angular accelerations induced only by shoulder flexion torque. Fig. 2b shows angular accelerations induced only by elbow flexion torque. (Adapted from Hirashima, 2011²⁾).

Fig. 3 Simulated motions of the two-joint (shoulder and elbow) system in a horizontal plane, when the same shoulder flexor torque is exerted in two different postures. (Adapted from Hirashima, 2011²⁾).

flexion and elbow *extension* for posture (a), whereas it induces shoulder flexion and elbow *flexion* for posture (b).

Thus, in order to estimate angular accelerations induced by joint torques in multi-joint movements, we need to pay attention not only to the joint torques, but also to the posture of the system. Mathematically speaking, instantaneous accelerations ($\ddot{\theta}^r = (\ddot{\theta}_1^r \ddot{\theta}_2^r)^T$) induced by joint torque can be calculated by multiplying the inverse of the system inertia matrix ($I(\theta)^{-1}$) to the torque vector ($\tau = (\tau_1 \tau_2)^T$) as follows: $\ddot{\theta}^r = I(\theta)^{-1} \tau$. This method is often called “induced acceleration analysis.”

The instantaneous effect in n-DOF systems in 2D. The two properties described above are also applicable to systems with more than 2 DOFs. Although the equation of motion with more than 2 DOFs is much more complex than Eq. 2 and Eq. 3, the equation of the n-DOF system ($n \geq 3$) can always be written in the following form:

$$\begin{pmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \vdots \\ \ddot{\theta}_n \end{pmatrix} = \begin{pmatrix} I_{11} & I_{12} & \cdots & I_{1n} \\ I_{21} & I_{22} & \cdots & I_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ I_{n1} & I_{n2} & \cdots & I_{nn} \end{pmatrix}^{-1} \left\{ \begin{pmatrix} \tau_1 \\ \tau_2 \\ \vdots \\ \tau_n \end{pmatrix} + \begin{pmatrix} V_1(\theta, \dot{\theta}) \\ V_2(\theta, \dot{\theta}) \\ \vdots \\ V_n(\theta, \dot{\theta}) \end{pmatrix} + \begin{pmatrix} g_1(\theta) \\ g_2(\theta) \\ \vdots \\ g_n(\theta) \end{pmatrix} \right\} \quad (9)$$

It can be written more simply as follows:

$$\ddot{\theta} = I(\theta)^{-1} \{ \tau + V(\theta, \dot{\theta}) + g(\theta) \} \quad (10)$$

Because this equation is in the same form as Eq. 6 in the 2-DOF system, we can discuss the cause-and-effect relationships between joint torques and accelerations in a similar way as for the 2-DOF system. In general, the mechanisms by which joint torques induce angular accelerations can be graphically summarized as shown in Fig. 4. This figure indicates the following:

- 1) A joint torque at each joint induces acceleration not only at its own joint (i.e., direct effect, solid line) but also at other joints (i.e., remote effect, dotted line).
- 2) Effects induced by joint torque depend on the posture of the whole system.

Thus, for example, in the case of a 3-DOF system

Fig. 4 Schematic figure of how joint torque at each joint induces angular accelerations at all joints in n-DOF system. (Adapted from Hirashima, 2011²³).

(shoulder, elbow, and wrist joints), the shoulder joint torque instantaneously accelerates not only the shoulder, but also the elbow and wrist joints.

The cumulative effect. This far, we have explained how joint torque at a certain instant induces angular accelerations on the system at that instant. However, the effect of joint torque is not limited to instantaneous accelerations, because the accelerations accumulate and remain in the system as a velocity. The velocity-dependent torques ($V(\theta, \dot{\theta})$) such as Coriolis and centrifugal torque can also induce angular accelerations. Angular accelerations induced by a velocity-dependent torque at a certain instant are expressed as follows:

$$\ddot{\theta}^v = I(\theta)^{-1} V(\theta, \dot{\theta}) \quad (11)$$

It should be noted that because angular velocity is an integrated value of angular acceleration, acceleration induced by a velocity-dependent torque at a certain instant (Eq. 11) reflects the cumulative effects of all muscles and gravity torques that have been previously applied to the system until that instant.

In summary, induced acceleration analysis suggests that angular acceleration at a certain instant is a collection of 1) the instantaneous effect induced by the joint torques and gravity torque at that instant and 2) the cumulative effect of all the joint torques and gravity torque applied to the system until that instant (Fig. 5).

Application to baseball pitching. Finally, we applied induced acceleration analysis to the motion of pitching a baseball to understand the kinetic mechanisms involved when skilled baseball players generate highball velocity. We considered a serially linked four-segment model of the trunk and an upper limb that had a total of 13 DOFs (Fig. 6a). There were three translational DOFs and three rotational DOFs for the trunk, three rotational DOFs for the shoulder, two rotational DOFs for the elbow, and two rotational DOFs for the wrist (for details see the legend of Fig. 6).

Fig. 6b shows the contributions of the 13 DOF velocities to fingertip velocity in skilled baseball players at the instant the ball is released³¹). Our kinematic analysis revealed that the velocity of ball release was mainly produced by the leftward rotation of the trunk, internal rotation of the shoulder, elbow extension, and wrist flexion.

Next, we examined the kinetic mechanism of how these joint rotations were accelerated. The equation of motion for this 13-DOF system was written as follows:

$$\ddot{\theta} = I(\theta)^{-1} \{ \tau + V(\theta, \dot{\theta}) + g(\theta) \} \quad (12)$$

where $\ddot{\theta}$, τ , $V(\theta, \dot{\theta})$, $g(\theta)$ are 13-dimensional vectors, and $I(\theta)$ is 13-by-13 matrix for the 13-DOF model used here. This equation shows that the j^{th} angular acceleration ($\ddot{\theta}_j$) is produced by the instantaneous direct effect ($\ddot{\theta}_j^r$), instantaneous remote effect ($\ddot{\theta}_j^{rk} (k \neq j)$), cumulative effect ($\ddot{\theta}_j^v$), and

Fig. 5 Block diagram of the generation mechanism of multi-DOF human motion. (Adapted from Hirashima et al., 2008³²⁾).

Fig. 6 (a) 13-DOF model. (b) Contributions to the translational velocity of the fingertip at the time of ball release. There are 13 contributors to the fingertip velocity. C: translation of the trunk including three degrees of freedom (DOF) (forward-backward, upward-downward, and right-left); AP: anterior(+)-posterior(j) lean; ML: medial(+)-lateral(j) tilt; TW: left(+)-right(j) twist of the trunk; IE: internal(+)-external(j) rotation; ED: elevation(+)-depression(j); k: third-axis rotation of the shoulder; EF: extension(+)-flexion(j); PS: pronation(+)-supination(j) of the elbow; FE: flexion(+)-extension(j); UR: ulnar(+)-radial(j) deviation of the wrist. (Adapted from Hirashima, 2007³¹⁾).

instantaneous effect from gravity torque ($\ddot{\theta}_j^g$), as expressed in the following:

$$\begin{aligned} \ddot{\theta}_j &= \sum_{i=1}^{13} A_{ji} \tau_i + \sum_{i=1}^{13} A_{ji} V_i + \sum_{i=1}^{13} A_{ji} g_i \\ &= (\ddot{\theta}_j^{\tau 1} + \ddot{\theta}_j^{\tau 2} + \cdots + \ddot{\theta}_j^{\tau 13}) + \ddot{\theta}_j^V + \ddot{\theta}_j^g \end{aligned} \quad (13)$$

where A_{ji} is the (j, i) component of the matrix $I(\theta)^{-1}$.

Applying this analysis to pitching a baseball, Hirashima et al.³²⁾ revealed that the motions of proximal joints (trunk and shoulder) are produced by their respective joint torques (i.e., instantaneous direct effect, solid line in Fig.

4); that is, the trunk leftward rotation is accelerated by the trunk leftward rotation torque, and the shoulder internal rotation is accelerated by the shoulder internal rotation torque. In contrast, distal joint rotations (elbow extension and wrist flexion) are mainly produced by velocity-dependent torques.

We further examined which segment motion is the source of the velocity-dependent torque acting on the elbow and wrist accelerations by decomposing the velocity-dependent torque into various individual kinematic sources. Results showed that the velocity-dependent torques at the elbow and wrist were produced by the forearm angu-

lar velocity that was originally produced by the trunk and shoulder joint torques in the earlier phase of the motion.

Taken together, the kinetic chain of events necessary to pitch a baseball can be summarized as follows. Firstly, the trunk forward motion and leftward rotation are accelerated by their respective joint torques (instantaneous direct effect) produced by relatively large muscles located in the lower extremity and trunk (Fig. 7a). The shoulder horizontal flexion torque and internal rotation torque during this phase prevented the upper arm from lagging behind relative to the trunk. As a result, the angular velocity of the upper arm also increased with that of the trunk (Fig. 7b). Thus, the motions of the trunk and upper arm in the early phase are produced by the instantaneous direct effect of large proximal muscles. The angular velocities of the trunk and upper arm produced by the above mechanism are the sources of the velocity-dependent torque acting to produce elbow extension (Figs. 7c and 7d). As a result, elbow joint angular velocity increased, and concurrently, forearm angular velocity relative to the ground also increased. Forearm angular velocity subsequently accelerated elbow extension (Fig. 7e) and wrist flexion (Fig. 7f). Thus, angular velocities of the trunk and upper arm, produced by the proximal muscles in the early phase, remain in the loop of cumulative effects, and accelerate distal joint rotations in the later phase of the motion.

Importance of understanding cause-and-effect relationships in complex movements. Knowledge of how muscle forces produce joint rotations is fundamental to the fields of sports biomechanics and rehabilitation medicine. Although muscle activities, joint torques, and joint rotations themselves have been examined extensively in sports medicine³³⁻³⁵, a knowledge of the cause-and-effect relationships among these variables has not been fully

understood, because most of the previous studies have not distinguished between instantaneous and cumulative effects. Determining whether a joint angular acceleration is caused by an instantaneous or cumulative effect is very important, because the original cause of the acceleration is clearly different in terms of time; specifically, the cause of the instantaneous effect is the joint torque and gravity torque at that instant, whereas the cause of the cumulative effect is a function of all the joint torques and gravity torque applied to the system until that instant. As we demonstrated in this review, by using induced acceleration analysis we can determine the kinetic sources of each joint rotation and gain insight into the chain of causation of athletic movements and the control strategies adopted by high-performance athletes.

Organization of multi-limb rhythmic movements

When humans plan to coordinate continuous and rhythmic movements at high movement frequencies, the nervous system exhibits a characteristic coordination pattern that is spontaneously and autonomously formed and executed, regardless of the original intention, making multi-limb movements difficult to control. This characteristic of neural systems is well understood and is formulated by a theoretical approach called the *dynamical systems approach*³⁶. The dynamical systems approach was originally developed to describe a principle of pattern formation in complex systems. A dynamical system is a system with a pattern that evolves over time in a self-organized manner, and according to a principle that can be formulated by differential equations. Over the last three decades, there have been numerous reports that rhythmic movement coordination, regardless of what limbs are involved, obeys common and general dynamical principles of self-organization.

Fig. 7 Kinetic chain of baseball pitching. (Adapted from Hirashima, 2011²).

Dynamical modeling. Kelso^{3,37)} first demonstrated that a rhythmic coordination pattern is spontaneously and autonomously formed (*i.e.*, self-organized). He examined rhythmic, bimanual finger coordination in a phase transition paradigm^{3,37)}. In his experiment, the participants were instructed to perform adduction–abduction movements with both index fingers to a metronome beat in anti-phase, anti-symmetric mode (homologous muscle groups alternately contract). When movement frequency that was specified by a metronome beat increased to a critical frequency, sudden and abrupt phase transitions to in-phase, symmetric mode (homologous muscle groups simultaneously contract) occurred unintentionally.

Haken et al.³⁸⁾ modeled these phase transition phenomena using nonlinear oscillators according to the concept of synergetics³⁹⁾. Synergetics is an interdisciplinary theory that explains self-organized phenomena in terms of relationships between an order parameter that describes a macroscopic pattern of a system and a control parameter that leads the macroscopic pattern to transform into a different one³⁹⁾. Haken et al.³⁸⁾ modeled the phase transition in Kelso's experiment³⁾ by using the relative phase of both fingers as the order parameter, and movement frequency as the control parameter. This model is called the HKB (as in Haken-Kelso-Bunz) model (Eq. 14).

$$\dot{\phi} = -a \sin \phi - 2b \sin 2\phi \quad (14)$$

In this equation, the ratio b/a is equivalent to the movement frequency. In this potential function (Eq. 15), local minimum area and its depth are associated with the stability of the coordination pattern.

$$V(\phi) = -a \cos \phi - b \cos 2\phi \quad (15)$$

When movement frequency is low, which is expressed by $b/a = 1$, both in-phase (relative phase 0°) and anti-phase (relative phase 180°) activities are stable. As movement frequency reaches a critical point (as $b/a = 0.25$), phase transition from anti-phase to in-phase occurs, as expressed by the disappearance of the local minimum area of the relative phase of anti-phase.

Bistability of coordination pattern. Interestingly, this bistable nature of a coordination pattern, such as in-phase and anti-phase, exists irrespective of the limbs or joints that are being coordinated. For instance, in single limb wrist-elbow coordination, a coordination pattern where wrist flexion-extension synchronized with elbow extension-flexion was suddenly replaced with a coordination pattern in which wrist flexion-extension synchronized with elbow flexion-extension when movement frequency increased⁴⁰⁾. In addition, in action-perception coordination, such as synchronization of rhythmic finger movements to a metronome beat, extension-on-the-beat⁴¹⁾, or flexion-off-the-beat⁴²⁾, showed phase transition to the flexion-on-the-beat pattern when movement frequency increased. These studies suggest that movement frequency

is a common and critical parameter for the organization of various types of coordination.

The generic feature of bistability in rhythmically coordinated pattern formation can be modified by motor learning. Zanone and Kelso^{43,44)} first demonstrated this using bimanual finger coordination. In their experiments^{43,44)}, participants practiced relative phases other than in-phase and anti-phase coordination. As a result of this practice, the stability of the relative phase in question was enhanced. In fact, there have been numerous reports that intrinsically less stable (anti-phase) or unstable coordination patterns (relative phases other than in-phase and anti-phase) can be stabilized by practice for various types of coordination, including inter-limb coordination⁴⁵⁻⁴⁸⁾, intra-limb coordination⁴⁹⁾, action-perception coordination^{4,50)}, and multi-joint coordination that involves postural control⁵¹⁾.

Application of dynamical systems approach to actual rhythmic skills.

Quite recently, the dynamical systems approach has been applied to movement skills that are required in artistic performances such as in music and dance^{4,5,52)}. Fujii et al.⁵⁾ investigated bimanual movement in drumming performance. In their experiment, they determined that when novices intend to perform anti-phase bimanual drumming movements as rapidly as possible, they exhibited a phase wandering pattern (One hand tapped in succession and anti-phase pattern broke because of higher tapping rate of the dominant hand). On the contrary, professional drummers never showed this phase wandering pattern, and could maintain a rapid anti-phase pattern. By extending the HKB model (Eq. 14), Fujii et al.⁵⁾ revealed a relationship between the pattern of phase wandering in novice controls and the frequency difference of movement in both hands. First, they measured maximum hand movement frequency during unimanual tapping. Then, they incorporated the maximum frequency difference between both hands into the HKB model as follows:

$$\dot{\phi} = -a \sin \phi - 2b \sin 2\phi - c \sin(\phi - \psi) + \Delta\omega + d \cos \phi + \sqrt{Q}\xi_t \quad (16)$$

where $\Delta\omega$ is a detuning term that expresses the difference in maximum movement frequency between both hands, $c \sin(\phi - \psi)$ indicates an intention to keep the prescribed coordination pattern, and $d \cos \phi$ is the mean ϕ modification term that adjusts mean ϕ shift caused by the detuning term, and $\sqrt{Q}\xi_t$ denotes a Gaussian white noise process. The parametric change of the detuning term predicts the phase wandering pattern. This means that the phase wandering pattern during rapid bimanual tapping is related to the difference in maximum movement frequency between both hands during unimanual tapping.

Miura et al.^{4,52)} investigated basic movements of street dance using the dynamical systems approach. Creative performances by street dancers are mainly based on two types of basic coordination between movement and

the beat: down-on-the-beat and up-on-the-beat (Fig. 8). Down-on-the-beat is a coordination pattern where knee flexion is synchronized with the beat. Conversely, in an up-on-the-beat coordination pattern, knee extension is synchronized with the beat. Miura et al.⁵²⁾ investigated the coordination patterns of skilled street dancers and novice

controls within a phase transition paradigm similar to that of Kelso's experiment³⁷⁾. As a result, at low movement frequency, both groups maintained an up-on-the-beat pattern, and when movement frequency reached a critical value, a phase transition to down-on-the-beat occurred (Fig. 9). Interestingly, critical frequency in skilled

Fig. 8 Down-on-the-beat flexes the knees on the beat (a). Up-on-the-beat extends the knees on the beat (b). (Adapted from Miura et al., 2011⁴⁾)

Fig. 9 Relative frequency distribution of the phase angle of beat time that is superposed on movement trajectory on the phase plane that is composed of knee angular displacement and angular velocity in dancers (a) and nondancers (b). A phase angle between 0° and 180° indicates knee extension phase, and that between 180° and 360° indicates knee flexion phase. The top row illustrates the down-on-the-beat conditions; and both groups did not show phase transition. The bottom row illustrates the up-on-the-beat conditions; and both groups showed phase transition from up-on-the-beat to down-on-the-beat. (Adapted from Miura et al., 2013⁵²⁾)

street dancers is greater than in novices. In addition, when dancers and nondancers were required to maintain up-on-the-beat coordination at a high movement frequency (*i.e.*, 180 beats per minute), only the dancers were able to resist phase transition to down-on-the-beat coordination⁴⁾. Taken together, these findings suggest that there are intrinsic constraints of neural systems for pattern formation of coordination; one has to overcome these constraints in order to perform high-frequency rhythmic movements in music, dance, or sports.

Conclusions and future perspectives

Athletes in many sports highly value movement speed and quickness of response as routes to outperform their competitors. Musicians or dancers highly value high frequency movements because a wider variety of expressions can be possible by mastering such movements. More generally, given that we live in a constantly changing environment, the quick modification of ongoing fast movements is often required in order to thrive^{1,53,54)}. Russian physiologist Bernstein⁵⁵⁾ argued that quickness is the feature that dexterity achieves with considerable effort, but not something that a single property such as a fast-twitch fiber can attain. This fact underscores the necessity of conducting research on the science of movement that is highly interdisciplinary, including the fields of physiology, biomechanics, neurosciences, and behavioral sciences. We believe that understanding the neurophysiological and dynamical mechanisms underlying quick and fast movements that are mastered by skilled athletes⁵⁶⁾, can contribute not only to the enhancement of sports performance, but also to the facilitation of motor recovery and rehabilitation from neural damage. In this way, advances in the field will help athletes, coaches, and physical therapists develop better training and rehabilitation programs.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research (No. 25242059) to K.K.

References

- 1) Dawes J and Roozen M. 2011. *Developing Agility and Quickness*. Human Kinetics, IL, USA.
- 2) Hirashima M. 2011. Induced acceleration analysis of three-dimensional multi-joint movements and its application to sports movements. In: *Theoretical Biomechanics* (Klika V, ed), 303-318, InTech, Rijeka, Croatia.
- 3) Kelso JAS. 1981. On the oscillatory basis of movement. *Bulletin of the Psychonomic Society* 18: 63.
- 4) Miura A, Kudo K, Ohtsuki T and Kanehisa H. 2011. Coordination modes in sensorimotor synchronization of whole-body movement: A study of street dancers and non-dancers. *Hum Mov Sci* 30: 1260-1271.
- 5) Fujii S, Kudo K, Ohtsuki T and Oda S. 2010. Intrinsic constraint of asymmetry acting as a control parameter on rapid, rhythmic bimanual coordination: A Study of professional drummers and nondrummers. *J Neurophysiol* 104: 2178-2186.
- 6) Jennings JR, van-der-Molen MW and Steinhauer SR. 1998. Preparing the heart, eye, and brain: foreperiod length effects in a nonaging paradigm. *Psychophysiol* 35: 90-98.
- 7) Bower AC and Tate DL. 1976. Cardiovascular and skin conductance correlates of a fixed-foreperiod reaction-time task in retarded and nonretarded youth. *Psychophysiol* 13: 1-9.
- 8) Brunia CHM. 1993. Waiting in readiness: Gating in attention and motor preparation. *Psychophysiol* 30: 327-339.
- 9) Haagh SAVM and Brunia CHM. 1985. Anticipatory response-relevant muscle-activity, CNV amplitude and simple reaction-time. *Electroencephalogr Clin Neurophysiol* 61: 30-39.
- 10) Berardelli A, Rothwell JC, Thompson PD and Hallett M. 2001. Pathophysiology of bradykinesia in Parkinson's disease. *Brain* 124: 2131-2146.
- 11) Petersen SE, Robinson DL and Currie JN. 1989. Influences of lesions of parietal cortex on visual spatial attention in humans. *Exp Brain Res* 76: 267-280.
- 12) Liu XG, Ingram HA, Palace JA and Miall RC. 1999. Dissociation of 'on-line' and 'off-line' visuomotor control of the arm by focal lesions in the cerebellum and brainstem. *Neurosci Lett* 264: 121-124.
- 13) Miller AD and Brooks VB. 1982. Parallel pathways for movement initiation of monkeys. *Exp Brain Res* 45: 328-332.
- 14) Naito E, Kinomura S, Geyer S, Kawashima R, Roland PE and Zilles K. 2000. Fast reaction to different sensory modalities activates common fields in the motor areas, but the anterior cingulate cortex is involved in the speed of reaction. *J Neurophysiol* 83: 1701-1709.
- 15) Kudo K, Miyazaki M, Kimura T, Yamanaka K, Kadota H, Hirashima M, Nakajima Y, Nakazawa K and Ohtsuki T. 2004. Selective activation and deactivation of the human brain structures between speeded and precisely timed tapping responses to identical visual stimulus: an fMRI study. *NeuroImage* 22: 1291-1301.
- 16) Thobois S, Ballanger B, Baraduc P, Le Bars D, Lavenne F, Broussolle E and Desmurget M. 2007. Functional anatomy of motor urgency. *NeuroImage* 37: 243-252.
- 17) Kinomura S, Larsson J, Gulyas B and Roland PE. 1996. Activation by attention of the human reticular formation and thalamic intralaminar nuclei. *Science* 271: 512-515.
- 18) Paus T. 2001. Primate anterior cingulate cortex: where motor control, drive and cognition interface. *Nat Rev Neurosci* 2: 417-424.
- 19) Hopfinger JB, Buonocore MH and Mangun GR. 2000. The neural mechanisms of top-down attentional control. *Nat Neurosci* 3: 284-291.
- 20) Jennings JR and van der Molen MW. 2005. Preparation for speeded action as a psychophysiological concept. *Psychological Bulletin* 131: 434-459.
- 21) Pascual-Leone A, Vallssole J, Wassermann EM, Brasilneto J, Cohen LG and Hallett M. 1992. Effects of focal transcranial magnetic stimulation on simple reaction-time to acoustic, visual and somatosensory stimuli. *Brain* 115: 1045-1059.
- 22) Hilgetag CC, Theoret H and Pascual-Leone A. 2001. Enhanced visual spatial attention ipsilateral to rTMS-induced 'virtual lesions' of human parietal cortex. *Nat Neurosci* 4: 953-957.
- 23) Elbert T, Lutzenberger W, Rockstroh B and Birbaumer N.

1981. The influence of low-level transcortical DC-currents on response speed in humans. *Int J Neurosci* 14: 101-114.
- 24) Pascual-Leone A, Valls-Sole J, Brasil-Neto JP, Cohen LG and Hallett M. 1994. Akinesia in Parkinson's disease. I. Shortening of simple reaction time with focal, single-pulse transcranial magnetic stimulation. *Neurology* 44: 884-891.
- 25) Hummel FC, Voller B, Celnik P, Floel A, Giraux P, Gerloff C and Cohen LG. 2006. Effects of brain polarization on reaction times and pinch force in chronic stroke. *BMC Neurosci* 7: Article Number 73.
- 26) Valls-Sole J, Rothwell JC, Goulart F, Cossu G and Munoz E. 1999. Patterned ballistic movements triggered by a startle in healthy humans. *J Physiol Lond* 516: 931-938.
- 27) Maslovat D, Carlsen AN and Franks IM. 2012. Subcortical motor circuit excitability during simple and choice reaction time. *Behav Neurosci* 126: 499-503.
- 28) Ijiri T, Shinya M, Hagio K and Nakazawa K. 2013. The use of timing control strategies to overcome severe time constraints during rapid interception. *Proceedings in First International Congress on Sports Science Research and Technology Support*. Portugal: Setubal.
- 29) Vallderiola F, Valls-Sole J, Tolosa E, Ventura PJ, Nobbe FA and Marti MJ. 1998. Effects of a startling acoustic stimulus on reaction time in different parkinsonian syndromes. *Neurology* 51: 1315-1320.
- 30) Zajac FE and Gordon ME. 1989. Determining muscles force and action in multi-articular movement. *Exerc Sport Sci Rev* 17: 187-230.
- 31) Hirashima M, Kudo K, Watarai K and Ohtsuki T. 2007. Control of 3D limb dynamics in unconstrained overarm throws of different speeds performed by skilled baseball players. *J Neurophysiol* 97: 680-691.
- 32) Hirashima M, Yamane K, Nakamura Y and Ohtsuki T. 2008. Kinetic chain of overarm throwing in terms of joint rotations revealed by induced acceleration analysis. *J Biomech* 41: 2874-2883.
- 33) Hirashima M, Kadota H, Sakurai S, Kudo K and Ohtsuki T. 2002. Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *J Sports Sci* 20: 301-310.
- 34) Springings E, Marshall R, Elliott B and Jennings L. 1994. A 3-dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racquet-head speed. *J Biomech* 27: 245-254.
- 35) Fleisig GS, Andrews JR, Dillman CJ and Escamilla RF. 1995. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med* 23: 233-239.
- 36) Kelso JAS. 1995. *Dynamic patterns*. MIT Press, Cambridge, USA.
- 37) Kelso JAS. 1984. Phase transitions and critical behavior in human bimanual coordination. *Am J Physiol: Reg Integ Comp* 15: R1000-R1004.
- 38) Haken H, Kelso JAS and Bunz H. 1985. A theoretical model of phase transitions in human hand movements. *Biol Cybern* 51: 347-356.
- 39) Haken H. 1977. *Synergetics: An Introduction. Nonequilibrium phase transitions and self-organization in physics, chemistry and biology*. Springer-Verlag, Berlin.
- 40) Kelso JAS, Buchanan JJ and Wallace SA. 1991. Order parameters for the neural organization of single, multijoint limb movement patterns. *Exp Brain Res* 85: 432-444.
- 41) Carson RG. 1996. Neuromuscular-skeletal constraints upon the dynamics of perception-action coupling. *Exp Brain Res* 110: 99-110.
- 42) Kelso JAS, DelColle JD and Schoner G. 1990. Action perception as a pattern formation process. In: *Attention and Performance XIII* (Jeannerod M, ed), 139-169, Erlbaum, Hillsdale, NJ, USA.
- 43) Zanone PG and Kelso JAS. 1992. Evolution of behavioral attractors with learning: Nonequilibrium phase-transitions. *J Exp Psychol Hum Percept Perform* 18: 403-421.
- 44) Zanone PG and Kelso JAS. 1997. Coordination dynamics of learning and transfer: Collective and component levels. *J Exp Psychol Hum Percept Perform* 23: 1454-1480.
- 45) Kelso JAS and Zanone PG. 2002. Coordination dynamics of learning and transfer across different effector systems. *J Exp Psychol Hum Percept Perform* 28: 776-797.
- 46) Smethurst CJ and Carson RG. 2001. The acquisition of movement skills: Practice enhances the dynamic stability of bimanual coordination. *Hum Mov Sci* 20: 499-529.
- 47) Swinnen SP, Lee TD, Verschueren S, Serrien DJ and Bogaerts H. 1997. Interlimb coordination: Learning and transfer under different feedback conditions. *Hum Mov Sci* 16: 749-785.
- 48) Wenderoth N, Bock O and Krohn R. 2002. Learning a new bimanual coordination pattern is influenced by existing attractors. *Mot Contr* 6: 166-182.
- 49) Buchanan JJ. 2004. Learning a single limb multijoint coordination pattern: the impact of a mechanical constraint on the coordination dynamics of learning and transfer. *Exp Brain Res* 156: 39-54.
- 50) Ryu YU and Buchanan JJ. 2009. Learning an environment-actor coordination skill: visuomotor transformation and coherency of perceptual structure. *Exp Brain Res* 196: 279-293.
- 51) Faugloire E, Bardy BG and Stoffregen TA. 2006. Dynamics of learning new postural patterns: Influence on preexisting spontaneous behaviors. *J Mot Behav* 38: 299-312.
- 52) Miura A, Kudo K and Nakazawa K. 2013. Action-perception coordination dynamics of whole-body rhythmic movement in stance: A comparison study of street dancers and non-dancers. *Neurosci Lett* 544: 157-162.
- 53) Kudo K and Ohtsuki T. 1998. Functional modification of agonist-antagonist electromyographic activity for rapid movement inhibition. *Exp Brain Res* 122: 23-30.
- 54) Kudo K and Ohtsuki T. 2008. Adaptive variability in skilled human movements. *Inform Media Tech* 3: 409-420.
- 55) Bernstein NA, 1996. On dexterity and its development. In: *Dexterity and its development* (Latash ML and Turvey MT, eds), 1-244, Lawrence Erlbaum, NJ, USA.
- 56) Nakata H, Yoshie M, Miura A and Kudo K. 2010. Characteristics of the athletes' brain: Evidence from neurophysiology and neuroimaging. *Brain Res Rev* 62: 197-211.