BIOMECHANICAL REFLECTIONS ON TEACHING FAST MOTOR SKILLS

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Learning to perform a novel movement is believed to require the formation of an internal motor memory model in the central nervous system. This internal model is subsequently used to control the movement, i.e. coordinate muscle generated moments with non-muscle generated moments in order to execute the intended movement. A substantial part of the non-muscle generated moments acting on each segment in a fast unloaded movement arises due to movement of adjacent segments. If a complex novel movement is taught either in slow motion or by splitting it into partial movements, these intersegmental moments will not be present, and hence not accounted for in the internal motor memory model. It is suggested that coaches take this into account when methods for teaching fast motor skills are considered.

KEY WORDS: teaching, kicking, intersegmental dynamics, memory model

INTRODUCTION: Learning to perform a novel movement is believed to require the formation of a so-called internal model or motor memory in the central nervous system (Shadmehr & Mussa-Ivaldi, 1994). The internal model can be understood as a neural representation of the movement, a tool the nervous system uses to predict the forces that would be acting on the involved body parts during the intended movement, and to predict the motor patterns that should be produced to successfully execute the movement (Shadmehr & Thoroughman, 2000). The forces acting on the body comprise external forces imposed by the environment and internal forces arising within the musculo-skeletal system itself. Internal forces include those produced by stretch and compression of various tissues, and intersegmental forces imposed on each body segment by movement of adjacent segments. The role played by the intersegmental forces in movement dynamics is a frequent topic in the motor learning literature, where a common experimental design involves some sort of planar arm movement, e.g. pointing or reaching (examples of recent studies are Krakauer *et al.* (1999); Sainburg *et al.* (1999)). Generally, the magnitude of the intersegmental forces depends on the masses and accelerations of the moving segments (explained subsequently in Methods).

Just as the initial learning of a movement is believed to require formation of an internal model, adaptations to changes in the dynamics of the learned movement has been postulated to occur through recalibration of the internal model (Shadmehr & Mussa-Ivaldi, 1994). As the main mechanism currently believed to underlie memory formation and recalibration is long-lasting changes in synaptic efficacy (Bliss & Collingridge, 1993), it would seem advantageous to - so to speak - get the internal model right the first time.

Coaches frequently teach complex movements by splitting the entire movement into several partial movements, and having the athletes practice each partial movement isolated from the rest. The rationale is that learning a particular detail is facilitated by allowing the athlete to concentrate on it, relieved from the distraction of getting it to function in unison with all the other details of the entire movement. While this might seem reasonable, it does not address the problem of putting the details back together. Even if the central nervous system was capable of concatenating the formed internal models of each partial movement, the resulting integrated internal model would not necessarily contain the neural representation of the intersegmental forces present in the full movement, and hence not optimally adapted to its intended purpose. In other words, mastering the isolated details of a complex movement does not necessarily imply proficiency in the actual full movement.

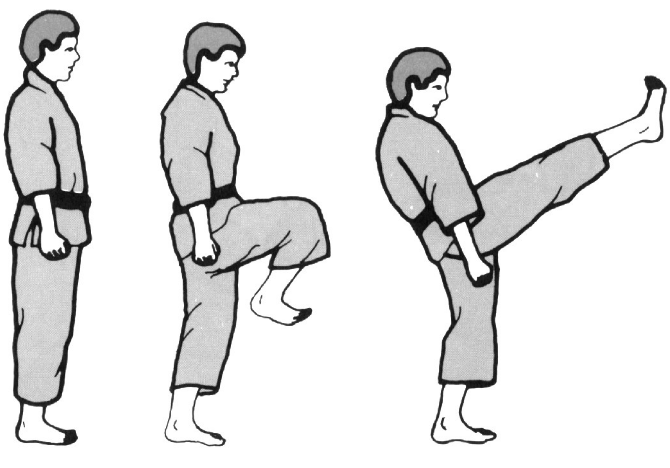
Among the numerous examples from sports, kicking is an activity where intersegmental dynamics can be expected to play a particularly significant role due to the larger mass of the leg as compared to the arm, combined with the very high velocities obtained in many types of kicking. In this study we investigated the martial arts high front kick. Although the front kick is among the least complex kicking techniques in martial arts, it does contain the necessary features to serve as experimental model for the problems outlined above. Firstly, it involves sequential movement of two segments, and hence the presence of intersegmental forces. Secondly, the sequential movements might be practised separately (Figure 1). Thirdly, it is very fast. Furthermore, martial arts kicks are scarcely represented in the literature. Thus, the immediate purpose of this study was to quantify the movement dependent intersegmental moments in the martial arts high front kick, and subsequently use the results as a basis for speculations on the role of intersegmental dynamics specifically in a martial arts kick teaching situation, but also in teaching situations of fast motor skills in general.

METHODS: Seventeen skilled taekwon-do practitioners participated as subjects (mean age 23.4 years (18-34), mean body mass 66.3 kg (46.4-79.4), mean height 173 cm (155-189), mean training experience 5.8 years (3-10)). Their skills ranged from club level to top European level. All the subjects gave informed consent to participate and the study was approved by the local ethics committee.

Execution of the basic high front kick starts from normal standing position with both feet on the ground. The kick is initiated by hip flexion of the kicking leg. While the thigh is moving upwards the knee flexes. When the thigh is oriented approximately horizontal but still moving upwards, the knee is flexed approximately 110°. From here the knee starts to extend. While the angular velocity of the shank is increasing, the angular velocity of the thigh decreases. The shank reaches maximum angular velocity at about 60° knee flexion, at which point the thigh is oriented approximately 40° above horizontal and its angular velocity is close to zero (Figure 1 and stick figure sequence in Figure 3). The ankle joint of the kicking leg is kept fully plantar-flexed and the toes fully dorsi-flexed in order to hit the target with the ball of the foot. During the kick, the supporting leg remains almost stationary on the ground. The kick is performed without body rotation (contrary to most other taekwon-do kicking techniques), which makes it suited for two-dimensional analysis. Each subject performed three kicks aimed at a tennis ball suspended from the ceiling and adjusted to the subject's chin level. The fastest kick from each subject was selected for further analysis.

The subjects were filmed from their right side while they kicked in a sagittal plane with a 16 mm high-speed camera (Teledyne DBM 45) operating at 200 frames per second. The camera was placed approximately 7 m from the subject. To identity body segments and joints during subsequent digitisation, markers were placed on the highest point on the iliac crest, the greater trochanter, the lateral epicondyle of the femur, the lateral malleolus and the fifth metatarsal head. After transferring the developed 16 mm film to videotape, the position co-

**Figure 1 - Frontal kick to the head. Correct execution of the kick can be envisioned as a smooth transition through the picture sequence. Practising the kick can be split into two partial movements. 1 - Hip flexion, stopping at the middle picture position; 2 - Knee extension, starting from the middle picture position.
The illustration is modified from Morris (1979).**



ordinates of the optical centres of the markers were automatically digitised (Peak Performance Technologies). The displacement data were filtered using a digital fourth-order Butterworth low-pass filter with zero degree phase lag (Winter, 1990). Optimal cut-of frequencies (6-10 Hz) were determined by use of residual analysis (Winter, 1990) and the Jackson knee method (Jackson, 1979). From the filtered displacement data, angular velocities and accelerations of the thigh and shank, as well as linear accelerations of the hip joint, were derived by finite difference calculation.
The kicking leg was modelled as a two-segment linkage with the shank and foot treated as one segment. This simplified the modelling and inverse dynamics calculations and has previously been applied in studies on kicking (Dunn & Putnam, 1988; Philips *et al.*, 1983; Putnam, 1993). For the model we used the equations of motion derived by Putnam (1983):

Shank:
$$
\begin{aligned}
(I_S+m_S\cdot r_S^2)\cdot\alpha_S = {} & M_K \\
& - m_S\cdot g\cdot r_S\cos\theta_S \\
& - m_S\cdot\omega_T^2 s_T\cdot r_S\sin\theta_K \quad \longleftarrow \\
& - m_S\cdot\alpha_T s_T\cdot r_S\cos\theta_K \\
& + m_S\cdot a_{Hx}\cdot r_S\sin\theta_S \\
& - m_S\cdot a_{Hy}\cdot r_S\cos\theta_S
\end{aligned}
$$

Thigh:
$$
\begin{aligned}
(I_T+m_T\cdot r_T^2)\cdot\alpha_T = {} & M_H \\
& - m_T\cdot g\cdot r_T\cos\theta_T + m_S\cdot g\cdot s_T\cos\theta_T + m_S\cdot g\cdot r_S\cos\theta_S \\
& - m_S\cdot\omega_T^2 s_T\cdot r_S\sin\theta_K \\
& - m_S\cdot\alpha_T s_T\cdot r_S\cos\theta_K + m_S\cdot\alpha_T s_T^2 \\
& + m_S\cdot\omega_S^2 r_S\cdot s_T\sin\theta_K \quad \longleftarrow \\
& + m_S\cdot\alpha_S s_T\cdot r_S\cos\theta_K + m_S\cdot\alpha_S r_S^2 + I_S\cdot\alpha_S \\
& + m_T\cdot a_{Hx}\cdot r_T\sin\theta_T + m_S\cdot a_{Hx}\cdot s_T\sin\theta_T + m_S\cdot a_{Hx}\cdot r_S\sin\theta_S \\
& - m_T\cdot a_{Hy}\cdot r_T\cos\theta_T + m_S\cdot a_{Hy}\cdot s_T\cos\theta_T + m_S\cdot a_{Hy}\cdot r_S\cos\theta_S
\end{aligned}
$$

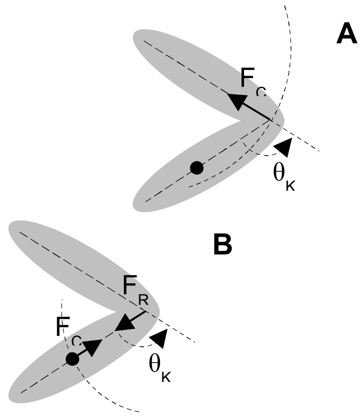


Figure 2

Nomenclature

θ: segment or joint angle	I: moment of inertia about CM	*Indices*
ω: angular velocity	m: mass	H: hip
α: angular acceleration	M: muscle moment	K: knee
a: linear acceleration	r: dist. from prox. end to CM	S: shank
g: gravitational acceleration	s: length	T: thigh

These equations are particularly suited for studying movement dependent intersegmental dynamics. Detailed elaborations of the equations were presented in Putnam (1991). As our results showed that the angular velocities of the segments were by far the most important causes of intersegmental moments, we will delimit the following explanation to the terms of the equations that express the angular velocity dependent intersegmental moments. Both equations are of the Newton/Euler form $I\cdot\alpha = \Sigma M$, where $I\cdot\alpha$ is the segment's moment of inertia about its proximal end multiplied by its angular acceleration, and ΣM is the summation of all moments acting upon the segment. Each moment term consists of mass times acceleration times moment arm. In the moment term from the shank equation marked with an arrow, m_s is shank mass; $\omega_T^2 s_T$ is squared thigh angular velocity times thigh length, i.e. the centripetal acceleration experienced by the proximal end of the shank when it travels the dotted circular path with angular velocity ω_T and radius s_T. Hence, $m_S\cdot\omega_T^2 s_T$ is the centripetal force (F_C in Figure 2A) acting on the proximal end of the shank. Finally, $r_S\sin\theta_K$ is the moment arm of F_C, where r_S is the distance from the proximal end of the shank to its centre of mass (CM), and θ_K is the knee flexion angle. Thus, the entire term quantifies a moment that accelerates the shank forwards with a magnitude depending on thigh angular velocity. Similarly, in the moment term from the thigh equation marked with an arrow, $m_S \cdot \omega_S^2 r_S$ is the centripetal force (F_C in Figure 2B) acting on the shank CM, and $s_T \sin\theta_K$ is the moment arm of F_C; F_R is the reaction force to F_C, acting on the distal end of the thigh. Thus, the entire term quantifies a moment that decelerates the forward movement of the thigh with a magnitude depending on shank angular velocity.

RESULTS: Figure 3 presents the moments acting on the thigh and shank during the kicking movement for one representative subject. The resulting moment (Iα) as well as each moment term from the equations of motion are represented as separate curves labelled according to the accelerating movement quantities. The vertical dotted line indicates time of maximal shank angular velocity. In the thigh moment frame, positive values designate hip flexion moments. The resulting hip flexion moment (Iα) was almost exclusively generated by the large hip flexor muscle moment (M_H), but notice how hip flexion was heavily counteracted by the large negative intersegmental moment arising from shank angular velocity (ω_S). This intersegmental moment increased as the shank gained angular velocity and the knee angle approached 90°, where the moment arm is longest. In the shank moment frame, positive values designate knee extension moments. The large resulting knee extension moment (Iα) was generated partly by the knee extensor muscle moment (M_K) and partly by the intersegmental moment arising from thigh angular velocity (ω_T).

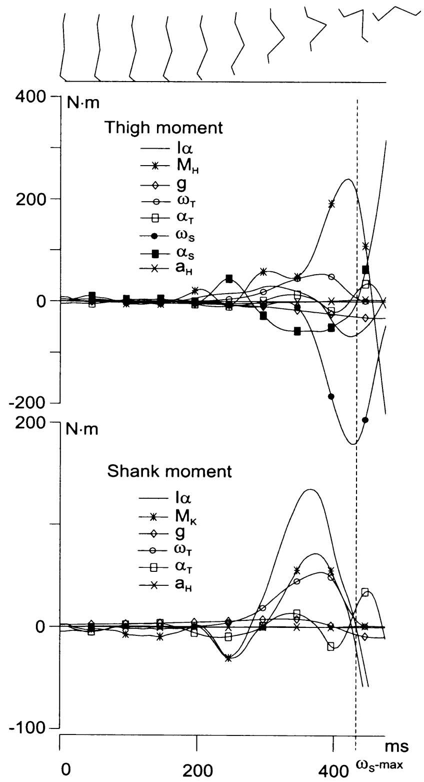


Figure 3

DISCUSSION: Our results show that velocity dependent intersegmental moments comprise a significant part of the movement dynamics during kicking. These moments would be smaller if the movement was performed in slow motion, or perhaps not present at all if the full movement was split into partial movements. Hence, learning the kick by these methods might not provide the central nervous system with the adequate sensory information for the formation of an optimal motor memory model. Complex movements can of course not be mastered immediately without practice, so it is obvious that some form of (simplifying) learning method is required. When the choice is between slow motion practice of the full movement and isolated practice of partial movements, we suggest that the former is better. This will at least retain some of the velocity caused intersegmental moments, and acknowledges Goodbody & Wolpert's (1998) finding that some internal model generalisation is possible across movement speeds. In conclusion, we suggest coaches teaching fast motor skills pay attention to (the absence of) velocity dependent intersegmental moments.

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