NEUROMOTOR CONTROL IN TAEKWONDO PRACTITIONERS OF DIFFERENT TRAINING LEVELS

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M.Phil

The Hong Kong Polytechnic University

2012

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Department of Rehabilitation Sciences

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Philosophy

August 2011

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it produces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

Polly Yee-Man Chung

ABSTRACT

Reaction time is an important part of neuromotor control mechanism which is regarded to be indicative of sports expertise. However, the effects of sports training on different components including premotor reaction time (PRT), electromechanical delay (EMD) and neuromotor delay were not well investigated. Taekwondo (TKD) is a hard-style martial art distinguished for its powerful kicking techniques. As a combat sport, neuromotor control of the body is an important factor in execution of powerful kicks and maintenance of balance during combat fighting. In light of the importance of neuromotor control and reaction time to the performance in this sport, this study examined the difference in total reaction time (TRT), PMT, EMD and neuromotor excitability in TKD practitioners of different skill levels and comparing them with non-athletes.

The first part of this study validated a method for measuring lower limb reaction time. The reliability and concurrent validity of an accelerometer were investigated. Twelve able-bodied subjects volunteered in this study. The lower limb movement onset time in response to an audio signal was measured by accelerometer and VICON 3D motion analysis system simultaneously. Each subject performed 5 trials and the test-retest reliability was assessed with $ICC_{3,1.}$

Agreement between the two instruments was assessed with $ICC_{2,1}$ and limits of agreement.

The mean motor reaction time measured by the accelerometer and VICON was 205.0ms and 196.9ms, respectively. Good reliability was found in accelerometer with ICC value equals to 0.739 ($p<0.001$). The mean difference in movement onset time between two instruments was 8ms and there was good agreement with mean ICC value of 0.77. The 95% limits of agreement between the two instruments ranged from -56.4 to 72.5ms.

It is concluded that accelerometer is a reliable tool for measuring lower limb movement onset times. However, the limits of agreement between the measurements recorded by the instruments were large, thus the absolute movement onset timing derived from these methods should not be used interchangeably.

The main study consisted of three groups, namely, professional TKD practitioners (n=20), amateur TKD practitioners (n=20), and non-athletes (n=20). The reaction times of rectus femoris (RF) and flexor pollicis brevis (FPB) in response to audio stimulus, general and sport-specific visual stimuli were tested. The audio stimulus was a plain 'beep' sound, the general visual stimulus was a coloured circle appearing randomly on a computer screen, whereas the sport-specific stimulus was an attack motion image preceded by images of an TKD athlete in guarding position presented in random order on a computer screen. Movement onset of the thumb and leg were detected by the subject pressing a thumb switch with the dominant hand and kicking the dominant leg, respectively. Surface electromyography (EMG) of FPB and RF were recorded. The TRT was measured from the onset of stimulus to movement onset. The time between appearance of the stimuli and EMG onset was denoted as PMT and the time lapse between EMG onset and movement onset was the EMD.

Neuromotor excitability was measured with the electrical stimulation strength duration testing. FPB and RF were electrically stimulated by square wave stimulus with inter-pulse duration of 1 second. The current intensity that induced minimal muscle contraction at pulse duration 200ms was defined as rheobase and this was compared among the groups. The differences in TRT, PMT, EMD and rheobase between three groups were analyzed with ANCOVA with body height as the covariate.

Results showed that professional TKD practitioners have shorter TRT than non-athletes with sport-specific visual stimuli but they have longer PRT and TRT in response to audio stimuli than amateur practitioners and non-athlete groups. Professional practitioners have significantly longer EMD than amateurs

to audio ($p=0.032$) and sports-specific visual stimuli ($p=0.03$) in FPB. Professional TKD practitioners have lower rheobase in RF ($p<0.001$) and higher rheobase in FPB ($p<0.001$) than amateurs and non-athletes.

From the present results, it is concluded that professional TKD practitioners have faster reaction to sports-specific stimulus in both the trained and untrained muscles and higher neuromotor excitability in the trained muscles. They react slower to non-sport specific stimuli, which suggested a decreased sensitivity to irrelevant sensory inputs after intensive TKD training.

CONFERENCE ABSTRACTS & PUBLICATIONS ARISING FROM THE THESIS

A. Journal Articles

1. Chung PYM, Ng GYF. Comparison between accelerometer and 3D motion analysing system in detecting movement. *Physiotherapy*. (Accepted for publication)
2. Chung PYM, Ng GYF. (2012) Taekwondo training improves the neuromotor excitability and reaction of large and small muscles. *Physical Therapy in Sport,* 13:163-169.

B. Conference abstracts

1. Chung PYM, Ng GYF (2010) Effects of Taekwondo training on neuromotor control of large and small muscles. *2010 Asics Conference of Science and Medicine in Sport*. 3-6 November 2011, Port Douglas, Australia. In: *Journal of Science and Medicine in Sport* 13 (6) December 2010 Supplement 1. P. 87.
2. Chung PYM, Ng GYF (2010) Effects of Taekwondo training on neuromotor excitability and reaction of large and small muscles. *The 7th Pan-Pacific Conference on Rehabilitation & 2010 Graduate Student Conference on Rehabilitation Sciences*. 23-24 October 2010, Hong Kong. P. 27

ACKNOWLEDGEMENTS

I deeply thank my supervisor, Professor Gabriel Ng. This thesis would not have been completed without his diligent guidance and encouragements. Professor Ng’s enthusiasm in research has inspired me to pursue better analytical and critical thinking.

I would like to express my gratitude to Mr. Yat-Man Cheung, Mr. Shing-Chung Chan, Mr. Sik-Cheung Siu, Dr. Raymond Chung and all members from Professor Ng’s research team for their advice, assistance and technical support throughout my study. I also thank the Guangdong Province Heavy Athletics of Sport Training Center, the International Taekwondo Hong Kong Association and all subjects who have participated in this project for their valuable contribution. I would like to acknowldege and the financial support from The Hong Kong Polytechnic University for the research project and for my overseas conference trip.

Lastly, my family and close friends, Miss Julie Ng, Miss Sharon Ho and Miss Susan Wan, shall receive my heartfelt thanks for their great love and encouragements in motivating me to taking up and completing this study.

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LIST OF ABBREVIATIONS

3D	=	Three dimensional
ANCOVA	=	Analysis of covariance
ANOVA	=	Analysis of variance
BMI	=	Body mass index
cm	=	centimeter
dB	=	Decobel
EMD	=	Electomechanical delay
EMG	=	Electromyography/electromyographic
FPB	=	Flexor pollicis brevis
Hz	=	Hertz
ICC	=	Intraclass correlation coefficient
kg	=	Kilo-gram
kΩ	=	Kilo-ohm
RF	=	Rectus femoris
PRT	=	Premotor reaction time
MMG	=	Mechanomyography/mechanomyographic
MRT	=	Motor reaction time
MΩ	=	Mega-ohm
m	=	meter
mA	=	Milli-ampere
ms	=	Milli-second
MVC	=	Maximum voluntary contraction
n	=	Number
N	=	Newton
Na^+	=	Sodium ions
Na^+/K^+	=	Sodium/Potassium
K^+	=	Potassium ions
SD	=	Standard deviation
TKD	=	Taekwondo
TRT	=	Total reaction time
YMD	=	Yongmudo

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Chapter 1 Literature Review

1.1 Taekwondo

Taekwondo (TKD) is an ancient martial art that originated in Korea more than 2000 years ago. It began as an offensive skill mainly practiced by soldiers and warriors for physical training and defense in battle. With the invention of modern ballistic weapons, TKD has since played a much less important role in military training and later became a folk sport for self-defence. Over the centuries, TKD techniques have been modified and evolved to become a systematic sport practised by 80 million people worldwide in more than 180 countries (WTF 2009), and it was adopted as an official competition event since the 2000 Sydney Olympic Games. The essential elements of TKD include the four catagories of basic skills and standardized patterns of martial techniques called 'poomsae'. The basic techniques of TKD are stance, blocks, kicks and strikes (Park et al., 1989). Stance forms the basis of other techniques as it provides stable support for powerful kicks and strike, while kicks are the most distinguishing features of TKD. The principles of TKD kicks emphasize on speed and power.

According to the rules of the World Taekwondo Federation, during international TKD competitions, contestants can score one point by attacking their opponents on their trunk protector by either the foot or fist. They can score two points by attacking with a turning kick that hits on the trunk protector and three points by a successful kick to the head, while penalty will be imposed if a contestant attacks other body parts of the opponent, falls down or avoids the match. These rules encourage the use of kicking techniques, thus offensive kicks are the most frequent techniques used to score in TKD competitions (Kazemi et al., 2006).

1.1.1 Biomechanics of TKD kicks

Previous biomechanical studies revealed that TKD kicks were generally more powerful and faster than those of other martial arts. An enormously high averge impact force of 9015N and execution time of 0.008s for a turning back kick performed by highly skilled TKD athletes were reported by Pedzich et al. (2006). Even though these figures were not reproduced in a later study by Falco et al. (2009) using a different measuring technique, the impact force and execution time were still reported to be 1994N and 0.254s, respectively. O'Sullivan et al. (2009) compared the biomechanical parameters of TKD with another kind of martial arts Yongmudo (YMD), which is a combination of TKD, Hapkido, Judo, Fencing and Ssireum, using 3D accelerometers. They found that the execution time of TKD turning kick to be 0.33s, which was shorter ($p<0.05$) than that of YMD of 0.4s despite the two kicks had similar impact force of 6400N (O'Sullivan et al., 2009). High level of neuromotor control ability is required in such powerful kicks with good control of body mechanics and balance.

1.1.2 Effects of TKD on motor performance

TKD training has been shown to improve motor performance in both young adolescents and elderly. Fong and Ng (2010) found that young TKD practitioners who have received long-term TKD training had better single leg standing balance and knee joint position sense comparing to the age-matched subjects. 11 weeks of TKD training has been shown to improve balance and walking abilities in community-dwelling elderly (Cromwell et al., 2007). Similarly, Brudnak et al. (2002) found improvement in single-leg standing balance, upper limb muscle strength, trunk flexibility in elderly after 17 weeks TKD training.

As a combat sport, reaction time is an important aspect for good performance, but there has been only one logitudinal study that investigated the effect of TKD training on premotor and motor reaction time. Furthermore, that study was conducted on people with mental retardation (Song & An, 2004). In that study, ten subjects with mental retardation (mean age 18.8±1.8 years) were subjected to 7 months of TKD training that included 2 days of TKD form practice and one day of other exercises that aimed to improve physcial strength, flexibility, muscle strength and endurance. The TKD movements were simplified to reduce intensity and duration as the subjects with mental retardation have shorter attention span. The pre-post training values on premotor reaction time (PRT) and motor reaction time (MRT) were compared to 10 other age-matched control subjects who were mentally retarted and had not received the training. Results of that study showed that a 7-month TKD training has no significant effect on PRT, but it improved the motor reaction time (p=0.008) in the subjects. However, since that study was done on people with mental retardation, its finding cannot be directly applied to people with normal mentality.

Considering that TKD is a popular sport in which good neuromotor control is important to master the powerful kicking techniques and no previous study had examined the characteristics of TKD athletes, this sport was therefore studied in this project to investigate the different components of the neuromotor control mechanisms in TKD practitioners.

1.2 Reaction time

Reaction time is the time needed to execute a movement in response to a stimulus. It is an important index of sports expertise as it reflects the speed of perception, decision making and movement execution (Kida et al., 2005; Mori et al., 2002). Intensive athletic practice can improve perceptual-motor abilities and physical fitness (Schmidt & Wrisberg, 2004). Harmenberg et al. (1991) studied the reaction time of fencers at different skill levels and found that the performance of professional fencers during competitions were strongly, inversely correlated with the reaction time in fencing simulation tasks.

The relationship between skill level and reaction time has been an important area of sports performance research. Faster visual reaction time were also found in elite practitioners compared to novice practitioners in TKD (Lee et al., 2010), baseball (Kida et al., 2005), karate (Mori et al., 2002), handball (Lidor & Daniel, 1998), soccer (Helsen & Starks, 1999), and volleyball (Castiello & Umilta, 1992).

1.2.1 Reaction time and TKD athletes

Heller et al. (1998) studied the kinanthropometric and physiological profiles in black belt TKD athletes of the Czech national team and found that the athletes (11 males, 12 females) had significantly lower body fat content, better muscle strength, flexibility, aerobic, and anaerobic capacity as compared to the non-athletic population. They also found that the competitive performance was significantly correlated with their maximum power output in both genders. In addition, competitive performance was related to the visual reaction time of the dominant upper limb and ventilatory threshold in males and females, respectively. Very recently, Lee et al. (2010) compared the reaction movement and visual search pattern of expert, intermediate and novice TKD practitioners and found that TKD experts had faster reaction movement in response to 4 different images of kicking by self-selected techniques. In addition, experts have different eye movement patterns from the intermediates and novices in which they showed longer eye fixation time on the chest while intermediates and novices showed longer fixation time on the thigh. These findings suggested that, like other sports, reaction time is an indicator for the competitive level of TKD athletes and visual perception is one of the cognitive components contributing to the difference in sports performance .

1.3 Premotor reaction time

Total reaction time (TRT) is usually regarded as the total time interval between the appearance of a stimulus and the onset of a designated response. This can be divided into PRT and MRT (Schmidt & Lee, 1999), with the latter also known as electromechanical delay (EMD) (Cavanagh & Komi, 1979). By measuring the fractioned reaction time, more information from the central and peripheral components of the nervous system can be derived.

The PRT is the latency between the appearance of a stimulus and onset of muscle activity measured by electromyographic (EMG) activities (Schmidt & Lee, 1999), which involves the time required for neural signals transmission, perception, and decision making. For example, when a subject is asked to press a key in response to a light stimulus, the light signal received by the retina is converted into neural signal by the photosensitive cells, and then transmitted to motor cortex via the afferent axons where information processing, decision making and motor planning take place, then efferent neural signals are sent from the primary motor cortex to the muscle to execute the movement (Lundy-Ekman, 2007). The duration between the moment of the stimulus appears up to the moment of an efferent signal reaching the motor unit and triggering a motor unit action potential constitutes the PRT.

Ando et al. (2001) compared the visual reaction time between intermediate level university soccer team members (mean age 21.5 years) and other university students without sports training. They measured the PRT and EMD to light stimulus of two visual angles and two distances with EMG. The subjects responded to the light stimulus by key-press response and the EMG of the flexor-digitorum superficialis muscle was recorded. Their results showed that the PRT of intermediate soccer players was faster than the non-athletes in both central and peripheral visual angles, and there was no difference in TRT and EMD between the two groups. These findings suggested that the soccer players have faster perceptual response than the non-athletes.

Similar to Ando et al. (2001), Zwierko et al. (2010) also reported significantly faster PRT and TRT in volleyball players to light stimulus than the non-athletes using the Vienna Test System. The authors explained that it was due to the faster visual signal transmission in perceptual and central stage of information processing. However, the definition of PRT in Zwierko et al. (2010) was different from Schmidt and Lee (1999). The participants of Zwierko's (2010) study were to respond to the stimulus by moving a finger from a start key to a response key as fast as possible. The PRT was measured from the onset of the stimulus to the release of the start key, and movement time was recorded from the release of the start key to depression of the response key. Therefore, PRT reported by Zwierko et al. (2010) was actually the TRT as defined by Schmidt and Lee (1999).

Many studies have shown that athletes participating in open skill sports have better perceptual and cognitive abilities than novice and non-athletes (Abernethy & Zawi, 2007; Kioumourtzoglou et al., 1998; Mori et al., 2002; Muller et al., 2010). Mori et al. (2002) compared the different reaction times and anticipatory skills in karate athletes (n=6, mean age 21 years) and novice (n=7, mean age 28 years) with a sport-specific video. They found that karate athletes had shorter reaction time than novices with same accuracy when asked to decide the targeted body segment of the offensive action shown in the videos as fast as possible. In a second part of their study, they also found that karate athletes could predict the targeted body segment more accurately when only the initial part of the offensive actions was shown to them. Mori et al. (2002) concluded that karate athletes have better anticipatory skills, and they could extract useful information from their opponents' actions earlier than the novices.

More superior anticipatory skills were also found in athletes of cricket (Muller et al., 2010), squash (Abernethy, 1990), basketball (Kioumourtzoglou et al., 1998) and badminton (Abernethy & Zawi, 2007) in predicting the direction of the ball or the trajectory of an opponent's racket stroke. Expert badminton players could make use of localized kinematic information of the racquet and the lower body to predict the direction of badminton strokes, while novices were more dependent on the concurrent presentation of the upper body and lower body kinematics. This difference led to more accurate prediction of the stroke direction from earlier part of the opponents' movements (Abernethy & Zawi, 2007) and the researchers proposed that this finding was related to the experts' superior skill and experience in stroke production as movement perception and movement production shared the same codes in the brain.

Other than anticipatory skills, better memory-retention on sport specific information was found in volleyball players (Kioumourtzoglou et al., 2000) and basketball players (Kioumourtzoglou et al., 1998). These perception and cognitive abilities are all components of the central processing skills reflected in the PRT. Therefore, it can be deduced that elite athletes have shorter PRT than novices and non-athletes. Such a shortening in PRT would be crucial in the success in competitions or injury prevention for sports that require fast reactive responses.

1.3.1 Domain specificity of training effects on reaction time

A few researchers suggested that the effects of sports expertise on reaction time are domain-specific (Abernethy, 1996; Helsen and Starkes, 1999; Kioumourtzoglou et al., 1998). However, evidence on the notion of domain specificity for reaction time is controversial. Helsen and Starkes (1999) found that when images of a structured soccer game were shown to soccer players, experts could predict the optimal offensive moves faster and more accurately than the novices, whereas no difference in response time was found between the two groups to general visual stimuli. More recently, Borysiuk and Bailey (2007) compared the reaction time in expert (n=12, mean age 22.3 years) and novice fencers (n=15, mean age 12.8 years) to three kinds of stimuli, and found that fencers had the fastest reaction to tactile stimuli followed by acoustic and visual stimuli. In addition, significantly faster reaction in expert fencers were reported in tactile ($p<0.029$) and visual stimuli ($p<0.057$), but not to audio stimulus ($p<0.249$). The authors suggested that the use of fencing foil enhanced the reactions to tactile stimulation, which provides crucial signals of the opponent's movement to the athlete during fencing.

On the other hand, Mori et al. (2002) reported faster reaction time in athletes to both general and sport-specific stimuli. In that study, karate athletes were asked to indicate the targeted body segment of the offensive action shown in a video in sport-specific condition, by pressing a key with either the left hand or the right hand. They found shorter reaction time in both conditions in karate athletes (n=6, mean age 21 years) than the novices (n=7, mean age 28 years). Mori et al. (2002) proposed that the athletes have better ability in vertical discrimination which could be due to increase in sensitivity to vertical differences by learning of karate techniques according to vertical levels of the body. In addition, Kioumourtzoglou et al. (1998) found that elite water polo players (n=19, mean age 18.3 years) reacted faster than the non-athletes (n=21, mean age 19.6 years) when asked to move as quickly as possible in the direction of a signal appeared on the screen in front of them. The authors explained the difference in reaction time to general stimulus by the importance of continuous leg movements during water polo games.

As most reports have revealed faster reaction time to sport-specific stimulus in the athletes, this domain specificity for faster reaction time supported the concept of effects of sports training on the cognitive components of the neuromotor control mechanism. However, the faster reaction to general stimulus in the athletes found in other studies (Ando et al., 2001; Kida et al., 2005; Kioumourtzoglou et al., 1998; Nakamoto & Mori, 2008) implied that besides the sport-specific knowledge and perception, other aspects of cognitive abilities such as spatial discrimination as suggested by Mori et al. (2002) would also improve with training.

1.4 Electromechanical delay (EMD)

The latency between the onset of muscle activation and force production is defined as the EMD (Maclntosh et al., 2006). This delay is caused by a series of processses leading to muscle contraction, including 1) propagation of action potential along the muscle fibers through the T-tubular system; 2) release of calcium ions from the sarcoplasmic reticulum; 3) formation of actin-myosin cross-bridges, and 4) stretching of the series elastic components by the contractile components of the muscle fibers (Maclntosh et al., 2006). Within these series of physiological processes, stretching of the elastic components is believed to account for the major portion of EMD (Cavanagh & Komi, 1979). When the EMD timing in elbow flexors were compared between isometric, concentric, and eccentric muscle contractions, the EMD in eccentric contractions was 49.5 ms, which was significantly shorter ($p<0.001$) than concentric contractions of 55.5 ms and isometric contractions of 50.3 ms (Cavanagh & Komi, 1979). The authors suggested that the stretching of elastic components would account for the major portion of the delay in force production. Since the elastic components are already stretched in the muscles, therefore, during eccentric contraction, it would result in shorter EMD than the other modes of contraction.

The EMD phenomenon is found to be correlated with maximum voluntary contraction (MVC), rate of force production and musculo-tendinous stiffness (Grosset et al., 2009, Kubo et al., 2001, Zhou et al., 1995). A significant negative correlation between EMD and musculo-tendinous stiffness has been reported by Grosset et al. (2009). Therefore, shorter EMD indicates greater musculo-tendinous stiffness and higher rate of force production, which is favorable for the execution of fast movements among athletes.

1.4.1 Neuromuscular performance in athletes and non-athletes

Although EMD is closely related to the rate of force production of the muscle, and faster rate of force production would be favorable when performing rapid movements, there have only been very few studies investigating EMD in athletes. Kamen et al. (1981) found no difference in EMD between weight lifters and endurance athletes in knee extensors, and they reported that the EMD in weight lifters and endurance athletes was shorter than the results previously found in non-athletes.

Zhou (1995) compared the EMD, MVC, and rate of force production of vastus lateralis and rectus femoris in weight lifters (n=6), endurance athletes (n=6), and physically active non-athletes (n=6), and found different results. The EMD of maximum voluntary contractions in response to light signal, electrical stimulation, and patellar tendon reflex were measured with EMG. They found that the weight lifters had shorter EMD, higher MVC, and faster rate of force development than the endurance athletes and non-athletes in voluntary contractions, but not in stimulated contractions or reflex contractions. This study also demonstrated that EMD was correlated to MVC and rate of force production in voluntary contractions.

In another study done by Ando et al. (2001) which compared the EMD of intermediate soccer players with non-athletes, no difference was found between the two groups. In that study, the subjects responded to light stimulus by pressing a key and the EMD of flexor digitorum superficialis muscle was measured. Unlike PRT, EMD is a physiological process confined to the muscles and the effect of sports training on EMD may not be extended to the untrained muscles, which could be a possible explanation for the lack of difference found between the soccer players and non-athletes. However, no previous study had compared the EMD of trained and untrained muscles, thus this assumption needs to be further validated.

1.4.2 Exercise and EMD

It is suggested that exercise training affects MVC, rate of force development, and musculo-tendinous stiffness (Aagaard et al., 2002; Cornu et al., 1997; Hakkinen et al., 1985). All these may, in turn, affect the EMD. The prospective studies investigating the effects of exercise training on EMD have found different results. An early study by Hakkinen and Komi (1983) with 11 males had found an increase in maximum isometric force and a decrease in time to reach specific force levels of 300N and 400N in isometric knee extension after strength training. However, no change in EMD of knee extensors reflex contractions was found after 16 weeks of strength training at 80%-120% of one repetition maximum. Similarly, Kubo et al. (2001) reported an increase in MVC and rate of force production in eight healthy males (mean age 22.6±2.8 years) after 12 weeks of isometric knee extension training at 70% MVC. They also found a decrease in EMD and an increase in stiffness of human tendon after strength training. On the other hand, Zhou et al. (1996) reported no change in

EMD, peak force and peak rate of force development during isometric MVC of knee extension after 7 weeks of sprint cycling training in six healthy men (mean age 18.8 years). The authors attributed the lack of significant changes was due to the low sensitivity of isometric contraction test in detecting the effects of dynamic training on muscle contractile properties.

Grosset et al. (2009) compared the effects of plyometric training and endurance training on EMD and musculo-tendinous stiffness in two groups of sedentary college students and found strikingly opposite results in the 2 modes of training. With 10 weeks of plyometric training, the result was an increase in MVC and EMD of triceps surae produced by maximal electrical stimulation of the tibial nerve and a concomitant decrease in musculo-tendinous stiffness. However, with 10 weeks of endurance training, the results revealed no change in MVC, but a decrease in EMD and an increase in musculo-tendinous stiffness.

Although the above studies demonstrated that the EMD in athletes was shorter than non-athletes (Kamen, 1981; Zhou, 1995), results of the prospective studies on the changes in EMD after different types of exercise training are inconclusive due to small sample size, large variations in training protocol, and experimental setup (Table 1). Moreover, the duration of the

Table 1. Review table of the studies on effects of exercise training on electromechanical delay.

Study	Subjects	Type of training	Measurements	Results
Hakkinen and Komi, 1983	11 men with experience in weight training Mean age: 26.4 years	Squat lifting with 80%-120% of 1 RM 3 times per week for 16 weeks	1. MVC of isometric knee extension 2. Force-time characteristics of isometric knee extension 3. EMD of patellar reflex contractions	Increase in MVC of knee extension Decrease in time to reach specific force levels (300N and 400N) No change in EMD
Zhou et al., 1996	6 healthy men Mean age 18.8 years	4-10 bouts of 30-s intense sprint cycling with 3-4 minutes recovery time 3 times per week for 7 weeks	1. MVC of isometric knee extension 2. EMD of knee extension MVC 3. Force-time characteristics of knee extension MVC 4. Peak rate of force development	No change in MVC, EMD force-time characteristics and peak rate of force development
Kubo et al., 2001	8 healthy men Mean age 22.6 years	Isometric knee extension at 70% MVC 4 times per week for 12 weeks	1. MVC of isometric knee extension 2. EMD of knee extension MVC 3. Stiffness of the vastus lateralis tendon structures measured by ultrasonic imaging 4. Rate of torque development	Increase in MVC, rate of torque development and tendon structures stiffness. Decrease in EMD.
Grosset et al., 2009	9 sedentary college students Mean age 21.0 years	Plyometric training Twice a week for 10 weeks	1. MVC of isometric plantarflexion 2. EMD of stimulated contractions of triceps surae 3. MT stiffness calculated indirectly from angular stiffness and torque of quick-release movement measured by dynamometer 4. Rate of torque development	Increase in MVC, EMD and rate of force development. Decrease in MT stiffness.
	21 sedentary college students Mean age 21.3 years	Endurance training Twice a week for 10 weeks		No change in MVC. Increase in MT stiffness. Decrease in EMD and rate of force development.

training protocol ranged from 7-16 weeks, which is relatively short comparing to the athletes who have received years of sports training. Therefore, the effect of exercise training on EMD is still inconclusive and there is a need to further investigate the effects of long term specific sports training on EMD.

1.5 Neuromotor excitability

Neuromotor excitability is a measure of the biophysical properties of the nervous tissue, which is related to the function of sodium/potassium (Na^+/K^+) pumps and concentration gradient across the sarcolemma and T-tubular membranes (Yerdelen et al., 2006). Muscle contraction is activated when a peripheral nerve action potential is transmitted across the neuromotor junction and triggers an action potential in the muscle fiber. The excitation is caused by the influx of sodium ions (Na^+) and efflux of potassium ions (K^+) which depolarize the sarcolemma. The flow of Na^+ and K^+ across the cell membrane is closely regulated by Na^+/K^+ pumps located in the sarcolemma and T-tubules membrane (Lieber, 2002). During muscle contractions, the movements of Na^+ and K^+ across the cell membrane would lead to a net loss of K^+ and a gain of Na^+ by the muscle cells. Such a disturbance of Na^+, K^+ concentration gradient across sarcolemma is shown to hinder the recovery of excitability and decrease contractile force (Clausen, 1996).

Everts and Clausen (1994) demonstrated in rat soleus muscles that the maximum capacity of Na^+/K^+ pumps was reached during electrical stimulation, implying that Na^+/K^+ pumps may often work at maximum capacity and this is likely to limit the restoration of Na^+, K^+ concentration gradient, hence limiting the maintenance of excitability. The decline in excitability would consequently lead to muscle fatigue (McKenna et al., 2008). Moreover, previous studies (Brown et al., 1986; Nielsen & Clausen, 1994) had reported that when the Na^+/K^+ pumps were suppressed in rat and guinea-pig soleus muscles, the rate of force decline during muscle stimulation would increase. These findings implied that the capacity and concentration of Na^+/K^+ pumps can be limiting factors for the neuromotor excitability, affecting the contractile performance of the muscles.

1.5.1 Exercise and neuromotor excitability

The effects of exercise training on the neuromotor excitability have only been investigated indirectly via quantification of concentration of Na^+/K^+ pumps in muscle biopsy. Numerous studies have shown that exercise training would increase the concentration of Na^+/K^+ pumps of the muscle biopsies and such increase is dependent on the training intensity (Evertsen et al., 1997; McKenna et al., 1993; Medbø et al., 2001). Green et al. (1999) compared the effects of high-resistance strength training and sub-maximal endurance training on the neuromotor excitability in healthy untrained people. They found that the Na^+/K^+ pumps concentration for the strength training group and endurance training group increased by 16% and 22%, respectively after training. In addition, McKenna et al. (1993) found that the content of Na^+/K^+ pumps in vastus lateralis muscles had increased by 16% after 7 weeks of sprint training in six previously untrained male subjects.

Effects of physical training on Na^+/K^+ pumps have also been investigated in the athletic populations. Medbø et al. (2001) tested the Na^+/K^+ pumps concentrations before and after three months of high-resistance strength training with squat lifting in high school elite Alpine skiers and found a 15% increase in Na^+/K^+ pumps after training. Similarly, Evertsen et al. (1997) reported a 16% increase in Na^+/K^+ pumps concentration after both moderate and high intensity training in cross-country skiers. Evertsen et al. (1997) also found that the performance of elite cross-country skiers is related to Na^+/K^+ pumps concentrations.

The above findings suggest that neuromotor excitability can be improved by various kinds of exercise trainings at moderate to high intensity in both the non-athletic and athletic populations. However, the direct relationship between sports training and neuromotor excitability is yet to be investigated.

Since TKD training involved intensive practice of reactive powerful kicking and punching techniques, the neuromotor excitability of muscles, in particular, lower-limb muscles could be modulated through training. According to the findings of previous studies in athletes, it is hypothesized that the excitability of lower-limb muscles of TKD athletes would be higher than non-athletes.

1.5.2 Measurement of neuromotor excitability

Strength duration testing is a well publicized, non-invasive method to determine neuromotor excitability and the method was well established (Irnich, 2010). Strength duration test shows graphically the hyperbolic relationship between the minimum intensity of a square-wave stimulus required to elicit muscle contractions and the pulse duration. As the pulse duration increases, the intensity of stimulus required to elicit muscle contractions would decrease.

However, minimal amount of current is needed to trigger a muscle contraction even with a very long or infinite pulse duration under the all-or-none characteristic of the action potential generation (Robertson et al., 2006). This threshold of excitation current intensity is known as the rheobase that signifies the excitability of a muscle.

Strength duration testing has been used clinically to assess the state of lower motor neuron lesions and nerve injuries as the strength duration curve is different between innervated and denervated muscles (Friedli & Meyer, 1984, Robertson et al., 2006). More recently, strength duration testing has been used to investigate the pathophysiology of several diseases that were suspected to affect axonal excitability such as diabetes mellitus and renal failure (Yerdelen et al., 2006). An increase in rheobase was found in people with diabetes and neuropathy in comparison to normal controls, and the severity of neuropathy was correlated to the axonal excitability (Krishnan & Kiernan, 2005).

Kaczmarek et al. (2008) were the first group of researchers to investigate muscle excitability in musculoskeletal condition. They compared the rheobase between children with and without lateral patellar instability. The rheobase of vastus medialis muscles in children with lateral patellar stability was higher than that of the control subjects, indicating lower muscle excitability in patients with neuromotor dysfunction.

With an extensive search of the literature, rheobase has not been compared between athletes of different sports or between athletes and non athletes. It is therefore hypothesized that sports training involving repeated fast reactions would increase the neuromotor excitability.

1.6 Summary

Previous research has shown that professional athletes have faster reaction times, but the basis of how the level of skills affects different components of the neuromotor control mechanism is not well investigated. Firstly, most of the studies on reaction time had only measured TRT of the athletes (Kida et al, 2005; Lidor & Daniel, 1998; Mori, 2002; Zwierko et al., 2010), while the PRT and EMD were not differentiated. Thus, the effects of skill level on the cognitive ability and physiological mechanisms of the muscles cannot be identified. Secondly, previous studies had mainly examined reaction time of the upper limbs and there is a lack of study comparing the neuromotor control mechanism of the trained and untrained muscles. Therefore, whether the effects of skill level on neuromotor control is movement-specific, is not known. Thirdly, few researchers had advocated that sport-expertise is domain-specific (Abernethy, 1996; Helsen and Starkes, 1999; Kioumourtzoglou et al., 1998), but the findings of the reaction time of athletes to different types of stimuli are controversial. Also, neuromotor excitability is another component of the control mechanism which could be affected by exercise training (Evertsen et al., 1997; McKenna et al., 1993; Medbø et al., 2001), and this is related to the contractile performance of the muscles (Clausen, 1996). However, this has never been investigated in athletes. In light of the above, the following objectives were developed for the present study.

1.7 Objectives of this study

1. To measure the TRT, PRT and EMD of the trained and untrained muscles with reaction time testing to audio, general visual and sport-specific visual stimulus in both professional TKD athletes and amateur TKD practitioners.

2. To measure the neuromotor excitability of the trained and untrained muscles in both professional TKD athletes and amateur TKD practitioners.

3. To compare the PRT, EMD and neuromotor excitability between professional TKD athletes, amateur TKD practitioners and non-athletes.

1.8 Hypotheses of this study

1. As plenty of evidence has suggested that professional athletes have better cognitive ability than novices and non-athletes which leads to faster reactions, it is hypothesized that professional TKD practitioners have shorter PRT than the amateur TKD practitioners and non-athletes in both the trained and untrained muscles.

2. Since previous studies had proved that experienced TKD athletes had higher muscle strength than non-athletes and other sports players (Heller et al., 1998; Tsokovic et al., 2004), and MVC is negatively correlated with EMD (Zhou, 1995), it is hypothesized that professional TKD practitioners have shorter EMD than the amateur TKD practitioners and non-athletes in the trained muscles.

3. In view that the neuromotor excitability could be improved by exercise (Clausen, 1996; Green et al., 1999), it is hypothesized that professional TKD practitioners have higher neuromotor excitability than the amateur TKD practitioners and non-athletes in both the trained muscles.

1.9 Layout of this thesis

The thesis comprises two parts, the first part is to validate the use of accelerometer in measuring movement onset whereas the second part is the investigation of muscle reaction time and neuromotor excitability of profession and amateur TKD athletes, and non-athletes, which is the main study of this thesis. The final chapter is the grand discussion and conclusion of the two studies.

Chapter 2 Comparison between accelerometer and 3D motion analyzing system in detecting movement

2.1 Introduction

Reaction time is an important determining factor in many sporting events. Although there were a number of reports on reaction time, most of them only examined movements of the upper limbs (Ando et al., 2001; Dane et al., 2008; Kida et al., 2005; Mori et al., 2002; Nakamoto & Mori, 2008), possibly because upper limb reaction time can be conveniently measured by key-pressing response on a keyboard or using a thumb switch. However, these methods are not applicable to the lower limb.

It has been reported that the motor control between upper and lower limbs is different (Christou & Rodriguez, 2008). Christou and Rodriguez (2008) examined the transfer of motor performance between ipsilateral upper and lower limbs by measuring the force and time accuracy of goal-directed isometric contractions of the muscles and found a significant decrease in movement timing error after practice but no parallel change was observed in the error on force development. They also found that not all components of motor learning can be transferred between the upper and lower limbs. In order to thoroughly understand the effect of sports training on the motor performance of different body parts, it is necessary to measure the lower limb response to stimulus.

2.1.1 Previous methods for measuring lower limb reaction time

The methods of lower limb reaction time measurement vary greatly. Zhang et al. (2008) used a switch panel to assess the lower limb reaction time of a group of dancers. A switch panel with a start button and five stop buttons was put on the floor in front of the subject who was sitting on a chair. The subject needed to put the foot on the start button at the beginning of the test and when any of the stop buttons lit up, the subject would touch that stop button as fast as possible. Lidor et al. (1998) measured the reaction time of handball players with two specific designated carpets. Subjects needed to move two steps forward from one carpet to the other when a visual signal appeared. However, the responses in the above studies were not functional movements and not related to the sports training, which may not truly reflect the athletes' ability.

Another equipment reportedly designed to measure lower limb reaction time was a wrestling practice dummy with force sensor embedded in the center (Whitley & Montano, 1992). Subjects in that study attacked the target on the dummy upon seeing a visual signal. This method could simulate the sport-specific movement, but its applicability is restrictive to a specific athletic population only. The variability in experimental set-up also makes the comparisons of results from different studies difficult. Therefore, a method with wider applicability is needed.

2.1.2 Motion analysis system

Three-dimensional (3D) motion analysis technology has been widely used in studying gait and is regarded as the gold standard for analyzing movements (L'Hermette et al., 2008; McGinley et al., 2009; Pomeroy et al., 2006; Webster et al., 2005). Most 3D motion analysis systems use cameras to capture the trajectories of reflective markers attached to the body parts during movements. The spatio-temporal kinematics parameters of the movements can be acquired after data processing, thus it can be used to measure the onset timing of body movements. However, due to the complex set up and sophisticated equipment involved, this technology may not be easily applied in the clinical setting.

2.1.3 Acclerometer

Accelerometer is a relatively simple instrument that measures movements involving acceleration. Most accelerometers contain a piezoelectric element and a seismic mass embedded in a sensor case, and when the piezoelectric element is compressed or sheared by the seismic mass during acceleration, it will generate voltage signals proportional to the force. Movements can be detected by attaching an accelerometer to the appropriate body landmarks. The portability, simplicity and relatively low cost of an accelerometer make it an ideal equipment for movement detection and biomechanical analysis, in particular for the clinical setting.

Accelerometer has been used for studying movements such as gait (Lord et al., 2008), physical activities monitoring (Chen & Bassett Jr, 2005; Trost et al., 2005), body centre of mass estimation (Lee et al., 2007) and muscle activities with perturbation in postural testing (Ng, 2005). Good test-retest reliability has been reported for accelerometer recordings (ICC from 0.7 to 0.97) (Henriksen et al., 2004; Moe-Nilssen, 1998; Van Hees et al., 2009; Armstrong et al., 2010). Light and compact accelerometers are commercially available, thus it can be easily applied to different body parts to measure movements of both upper and lower limbs. However, validity of accelerometer in measuring reaction time has yet to be determined. Therefore, this study aimed to determine the intra-rater reliability of accelerometer and agreement between accelerometer and a 3D motion analysis system in measuring motor reaction time of the knee.

2.2 Methods

Twelve able-bodied subjects aged between 22 and 29 years (mean age 26 ± 2.3 years) with mean height of 164 ± 9.4 cm and mean weight of 58 ± 9.4 kg volunteered for this study. All subjects have the preference of using their right leg to kick a ball, thus this was operationally defined as the dominant leg in this study. This study was approved by the Human Subjects Ethics Sub-committee of the The Hong Kong Polytechnic University (Appendix I). The purpose and procedure was explained to the subjects and a signed consent form (Appendix II) was obtained from each subject before the test.

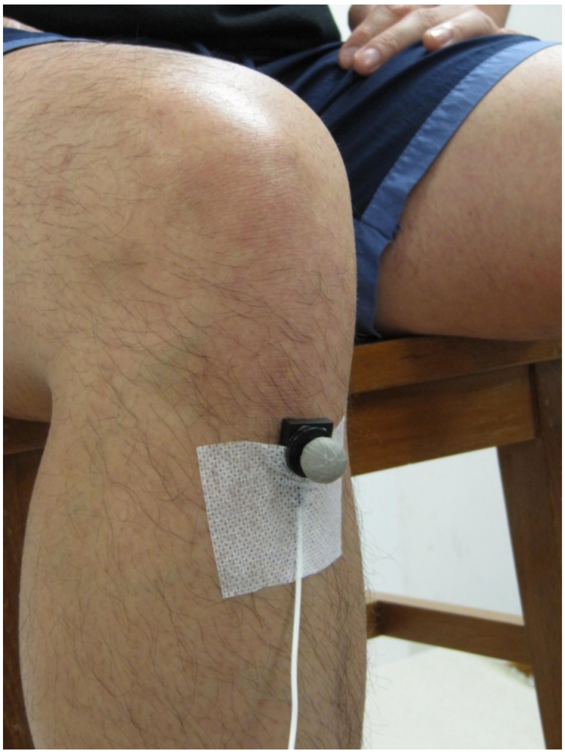
Lower limb movement onset time was simultaneously measured by a uniaxial, piezoelectric accelerometer (Model 8772A10, Kistler Instrument Corp., NY USA), and an 8-camera VICON motion analysis system (VICON v-370; Oxford, UK). The 8 cameras were mounted on the walls at 2 m above the floor in a laboratory of 4 m by 10 m. Subjects sat on a chair located in the center of the room with the sagittal plane aligned to the Y axis of the VICON system, and hip and knee flexed at 90°. The accelerometer was attached to the tibial tuberosity of the right leg and a spherical, reflective marker was placed over the accelerometer (Figure 1). Subjects were asked to extend their right knee as fast as possible once they heard a "beep" sound triggered by the operator.

The audio signal would appear at anytime from 1 to 8 seconds after a "start" verbal cue given by the operator. The audio signal was output to the VICON system via an analog to digital converter and displayed graphically as a voltage signal, so that the VICON system and accelerometer could be synchronized. Signals of the accelerometer were sent to an analog to digital converter at a sampling rate of 1000Hz and captured with LabVIEW software (National Instrument, TX, USA). The sampling frequency of the VICON cameras was set at 250Hz and VICON Nexus 1.4 (Oxford, UK) was used to reconstruct the sagittal trajectories of the reflective markers.

Both sets of data were exported to Microsoft Excel program for tabulation and data mining. Since accelerometer is an equipment that registers uniaxial force along the axis of movement, the antero-posterior trajectory of the reflective marker was therefore used for comparison. Movement onset was

Figure 1. The placement of acceleromotor and spherical reflective

marker on the tibial tuberosity of the right leg



defined as any deviation in the antero-posterior direction lasting for 5 ms or longer with at least 2 standard deviations (SD) difference as compared to the resting signal captured at 50ms before the audio signal for both sets of data.

2.3 Data analysis

Each subject was tested for 5 times and all the trials were used in the analysis. Paired t-test was used to compare the difference between movement onset time measured by accelerometer and VICON system. Reliability of the accelerometer and VICON was analyzed with intraclass correlation coefficient ($ICC_{3,1}$). The level of agreement between measurements was assessed with the $ICC_{2,1}$ and limits of agreement (Bland & Altman, 1986; Portney & Walkins, 2009).

2.4 Results

The movement onset time measurements are shown in Appendix III. The mean measurements of 5 trials for each subject are listed in Table 2. Results of paired t-test revealed no significant difference ($p=0.334$) between movement onset time measured by either method. The ICC values for the intra-rater

Table 2. Mean movement onset time measure by the accelerometer and VICON and the mean differences between the two measurements

	Mean values (SD) of the 5 measurements		Mean (95 % CI of the) difference between the two measurements#
Subject	Accelerometer	VICON	
1	179.2 (31.6)	194.6 (46.85)	-15.4 (-80.7 to 49.9)
2	249.0 (37.12)	228.4 (39.91)	20.6 (0.3 to 40.9)
3	186.6 (18.66)	189.0 (18.69)	-2.4 (-9.1 to 4.3)
4	196.4 (22.74)	159.8 (24.47)	36.6 (21.9 to 51.3)
5	272.4 (29.42)	224.8 (41.72)	47.6 (18 to 77.2)
6	253.4 (20.46)	201.8 (21.02)	53.6 (7.4 to 99.8)
7	156.4 (22.23)	140.6 (14.94)	15.8 (-37.3 to 68.9)
8	244.8 (23.48)	238.6 (34.16)	6.2 (-18.2 to 30.6)
9	160.2 (34.38)	159.8 (34.11)	0.4 (-70.2 to 71)
10	215.6 (27.63)	229.8 (28.91)	-14.2 (-43 to 14.6)
11	118.8 (21.56)	153.2 (21.37)	-34.4 (-25.4 to 43.4)
12	225.6 (16.24)	243.6 (19.84)	-18.0 (-6.2 to -29.8)

Mean of accelerometer measurement from 5 trials – mean of VICON measurement from trials

reliability of the accelerometer and VICON system were 0.739 ($p<0.001$) and 0.542 ($p<0.001$), respectively. The mean movement onset time measured with accelerometer was 205 (±46.6)ms, and that with VICON was 196.9 (±36.6)ms. The mean difference was 8ms. Values of $ICC_{2,1}$ between the two measurements ranged from 0.729 to 0.822 ($p<0.005$) (Table 3). Figure 2 is the Bland and Altman plots of all trials which examines if there is any bias in the two measurements and the plot shows the difference between two measurements against the mean values of the two methods.

2.5 Discussion

Good intra-rater reliability was found in both measuring methods for detecting movement onset and the ICC value for accelerometer measurement was higher than that of VICON system. The difference in sampling frequency between the two instruments may account for the discrepancy in reliability as it has been reported that measurement error of motion analysis would increase with a decreasing sampling frequency and an increasing movement speed (Polk et al., 2005). Therefore, accelerometer with higher sampling rate would provide more reliable measurements than 3D motion analysis system which has a lower

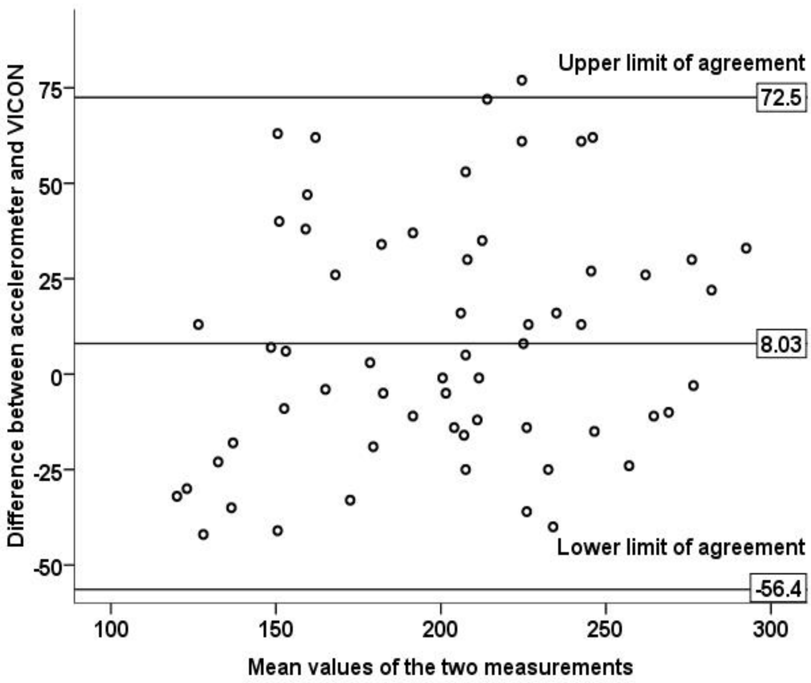
Table 3. Results of the agreement between accelerometer and VICON system

	ICC values	Mean (SD) difference between the two measurements#	Lower limit of agreement (ms)	Upper limit of agreement (ms)
Trial 1	0.745*	4.2 (32.9)	-60.3	68.7
Trial 2	0.729*	6.2 (34.0)	-60.5	72.9
Trial 3	0.758*	10.0 (34.2)	-57.0	77.0
Trial 4	0.822*	8.5 (33.1)	-56.4	73.4
Trial 5	0.817*	11.3 (30.1)	-47.7	70.4

Mean of accelerometer measurement from 12 subjects – mean of VICON measurement from 12 subjects

* Represents $p<0.005$

Figure 2. Differences of movement onset time between accelerometer and VICON (Accelerometer - VICON) versus mean values measured by accelerometer and VICON of all trials.



sampling frequency.

From the Bland and Altman plot (Figure 2) and results of ICC (Table 3), it showed that agreement between the movement onset time measured by accelerometer and VICON system was good, thus it implies that accelerometer and VICON are statistically interchangeable. However, the limits of agreement were quite large. Since the limits of agreement represent the 95% confidence range of values of the difference between two measurements, the present findings suggest that measurement of accelerometer may be 56.4ms earlier or 72.5ms later than that of VICON measurement. This range is considered clinically significant, thus the data obtained from the two instruments should not be used interchangeably.

Although no obvious bias was shown in the Bland and Altman plots (Figure 2), it is noted that the mean differences were closer to the upper limit of agreement in the Bland and Altman plot end and the values of difference from all five trials were positive. This is suggestive that there may be bias between the two equipment that the movement onset time measured by accelerometer is slower than by VICON. This could be due to difference in the mechanisms of the two equipment in detecting movements. Accelerometer detects force and translates it to movement, whereas the VICON system captures movements of the reflective markers per se. Signals from accelerometer are generated by deformation of the piezoelectric crystal inside the sensor when it is being compressed or sheared by the seismic mass during movement. Therefore, certain force is needed to deform the piezoelectric element before electric charges can be built up, and some time is needed for the voltage to reach a level detectable by the equipment. These might have led to the delay in reaction time measured by accelerometer.

2.6 Conclusion

It is concluded that accelerometer showed good reliability in measuring motor reaction time. However, the movement detected by an accelerometer was slower than that by a VICON system, thus the absolute value of movement onset timing detected by the two equipment with different sampling frequency should not be directly compared. Since accelerometer has the advantage of being a relatively simple technology suitable for detecting movements, its use in the clinical setting for movement studies is warranted.

Chapter 3 A study on the reaction time and muscle excitability of people with TKD training

3.1 Introduction

The background of the different components of the neuromotor control mechanism in athletes was discussed in Chapter 1. It was revealed that with training in sports that require reactive actions such as karate, soccer, and fencing, those athletes have faster reaction time and more superior anticipatory skills and sport-specific movement perception (Abernethy & Zawi, 2007; Ando et al., 2001; Borysiuk & Bailey, 2007; Mori et al., 2002). However, there were inconsistent evidence on the specificity of training effects, and limited evidence on other components of the neuromotor control mechanisms including electromechancal delay (EMD) and muscle excitability. Since understanding the effects of sports training on different components of the neuromotor control network would be beneficial to the development of training protocol and injury prevention, this study is to investigate the reaction time, EMD and muscle excitability in Taekwondo (TKD) practitioners at different training level.

In Chapter 2, the use of accelerometer to measure lower limb reaction time was validated, and the results showed that the accelerometer is a reliable equipment for measurement of lower limb movement onset. Since accelerometer is convenient to operate and could be applied to different body movements and setting, which allows comparison of results in future studies, this technology was used in the main study to measure lower limb reaction time.

3.2 Subjects

This study was done with a purposive sampling of 3 groups of participants. Group 1 included 20 professional TKD practitioners (15 males) aged 18-23 years (Mean age 19 years) who have received 3-11 years of intensive TKD training from the Guangzhou Provincial Sports Training Center of China. These subjects received TKD training 6 hours per day for 5 to 6 days per week. Group 2 included 20 amateur TKD practitioners (10 males) aged 19-24 years (mean age 21 years) from the TKD clubs of Hong Kong Institute of Vocational Education, Hong Kong University of Science and Technology, and The Hong Kong Polytechnic University. These participants have less than 3 years of TKD experience with 6-9 hours of training per week. Group 3 comprised 20 non-athlete controls (12 male) aged 19-29 years (mean age 23 years) and they were not involved in any regular sports training.

3.2.1 Inclusion criteria

1. 18-30 years old.
2. Professional TKD practitioners: More than 3 years of TKD experience.
3. Amateur TKD practitioners: 1-3 years of TKD experience.
4. Control subjects: Does not receive any regular sports training.

3.2.2 Exclusion criteria

Histories of surgeries or injuries requiring medical attention in the previous six months.

3.2.3 Logistics of the study

Data collection of the professional TKD practitioners was carried out in the Guangzhou Provincial Sports Training Center of China, whereas data collection for the other two groups were carried out at The Hong Kong Polytechnic University. The objectives and procedures of the study were explained to the subjects and written informed consent (Appendix IV) was obtained from the subjects prior to the test. This study was approved by the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University (Appendix V).

3.3 Details of the testing

In order to examine whether the effects of TKD training on reaction time is muscle-specific, both trained and untrained muscles were tested. Among various types of martial arts, TKD is distinguished by its fast and powerful kicking techniques, and TKD training involves intensive practice of the kicking techniques. Moreover, stronger knee extension strength in TKD practitioners comparing to novices and non-athletes has been reported (Heller et al., 1998; Toskovic et al., 2004). Therefore, the major knee extensor, rectus femoris (RF) was included in the testing as the trained muscle, while the small hand muscle, flexor pollicis brevis (FPB), which is seldom involved in TKD training, was included in the testing as the untrained muscle.

3.4 Reaction time testing

3.4.1 Type of stimulus

According to some previous studies, the faster reaction time and better performance in perception and cognitive abilities in athletes are domain–specific (Helsen & Starks, 1999; Borysiuk & Bailey, 2008; Kioumourtzoglou et al., 2000), faster reaction time are only found in response to sports-related stimulus such as pictures and films of the sports event that the athletes practice in. Therefore, both general and sports-specific stimuli were used to examine whether the effects of TKD training on reaction time is sports-specific as seen in other kinds of sports.

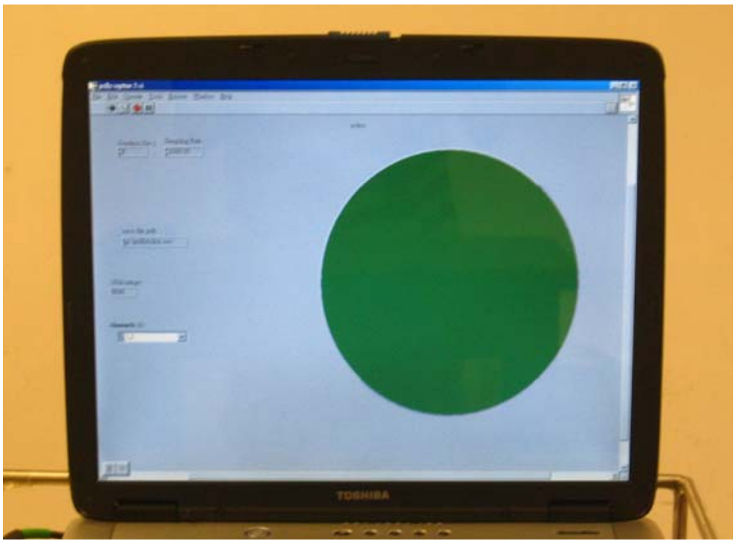
The non-sport specific stimuli comprised both audio and visual stimulations. The audio stimulation was a single beep sound on a quiet background, whereas the visual stimulation was a circle shown in a computer monitor which would change from dark green to light green colour with a grey background (Figure 3). For the sport-specific stimulus, it was a photograph of a TKD athlete performing a side kick preceded by a series of photographs of the athlete in guarding forms (Figure 4).

3.4.2 Measurement of the total reaction time

The movement onset timing (TRT) of the upper limb was detected by a thumb switch and that of the lower limb was measured by a uniaxial accelerometer (Model 8772A10, Kistler Instrument Corp, Amherst, NY, USA). The accelerometer was attached to the tibial tuberosity to register the antero-posterior force of knee extension. The validation on this measurement was done and the details were described in Chapter 2.

Figure 3. Illustration of the general visual stimulus

a. Start



b. End

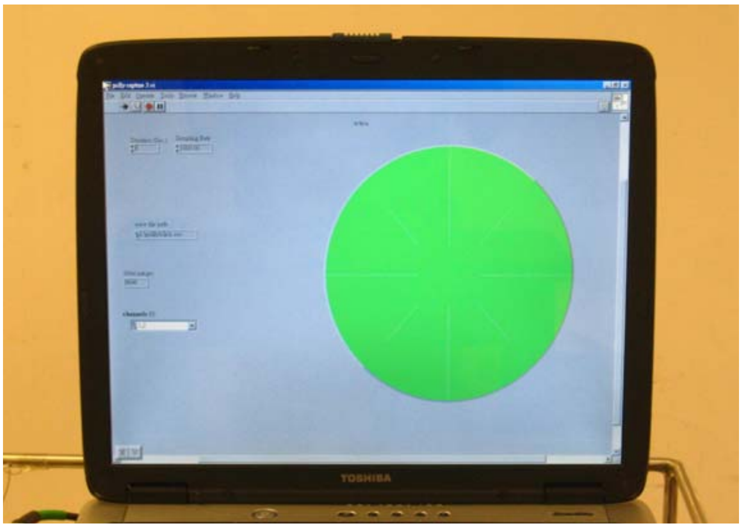


Figure 4. Illustration of sport-specific stimulus.

a. Series of pictures preceding the stimulus in guarding forms

b. Picture with the attacking action

3.4.3 Measurement of premotor reaction time

Premotor reaction time (PRT) was the latency between the appearance of stimulus and onset of muscle activities measured by electromyography (EMG). EMG signals of FPB and RF of the dominant limb were recorded by double-differential surface EMG with an inter-electrode distance of 3.5cm (BL-AE-WG, B&L Engineering, Santa Ana, CA, USA). The common mode rejection ratio of the electrodes was 95dB and input impedance was 100MΩ. The EMG signals were pre-amplified by 330 times and band-pass filtered between 10Hz and 312Hz. Dominant hand is defined as the one used for writing and dominant leg was defined as the one used for kicking a ball (Wong et al., 2009).

In order to reduce skin impedance, the skin over the recording site was shaved, gently abraded with fine sand paper and cleansed with alcohol. The skin impedance was checked after skin preparation to ensure the impedance to be less than 5kΩ (Gilmore & Meyers, 1983), otherwise the skin preparation procedure would be repeated. The electrodes were placed over midway between the anterior superior iliac spine and superior border of the patella for RF (Freriks et al., 1999) (Figure 5) and the thenar muscle for FPB (Udo et al., 2000) (Figure 6).

3.4.4 Testing procedure

Subject was positioned in sitting at 1.5m in front of a computer monitor with hips and knees flexed at 90° (Figure 7). The stimuli were delivered by the computer. A stimulus would appear randomly between 1 and 8 seconds after a "start" verbal cue for the non-sport specific audio and visual stimuli. For the sport-specific stimulus, each of the TKD images in guarding forms would appear on the screen for a randomised duration of 1-2 seconds before the "kicking" image. Upon the appearance of the respective stimulus, the subject would respond by pressing the thumb switch or kicking the dominant leg as fast as possible. The testing sequence was (1) audio stimulus, (2) general visual stimulus and (3) sport-specific stimulus. Each of the stimuli was tested 3 times.

3.4.5 Data acquisition

Amplified EMG signals together with signals from the thumb switch and accelerometer were sent to an analog-digital converter with a sampling rate of 1000Hz (DAQPad-6020E, National Instrument, TX, USA) and recorded by LabVIEW software (National Instruments, TX, USA) for off-line analysis. EMG onset was defined as a signal with at least 2 SD higher than the mean resting

Figure 5. Electrode placement on the rectus femoris of right leg

Figure 6. Electrode placement on the flexor pollicis brevis

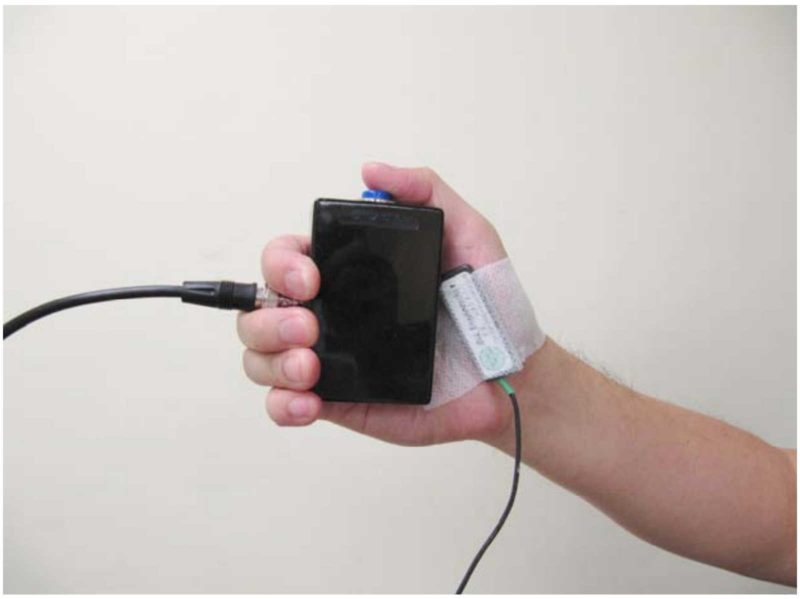
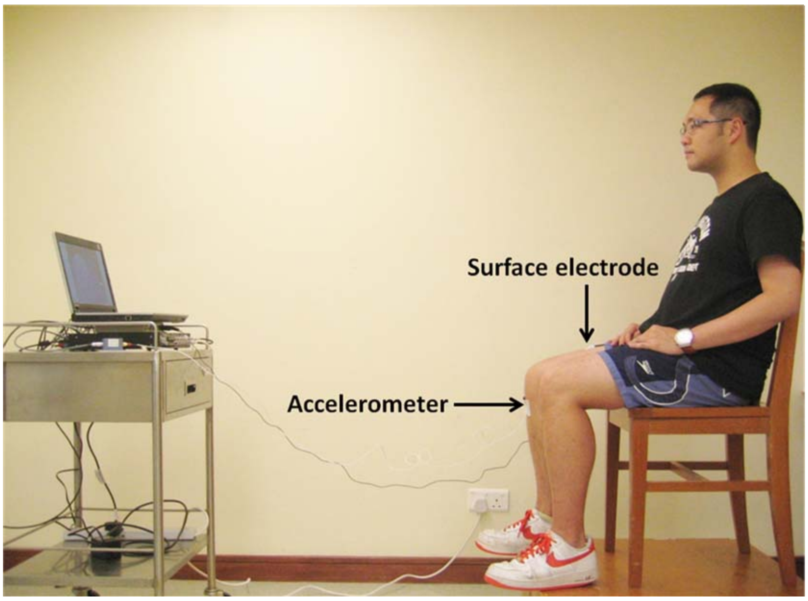


Figure 7. Experimental setup of the reaction time testing. The subject sat 1.5 m in front of the computer which delivered the three types of stimulus. The subject was positioned with hip, knee and ankle at 90° and back leaning of the back support. A surface electrode and an accelerometer were attached to the dominant leg to measure the lower limb movements.

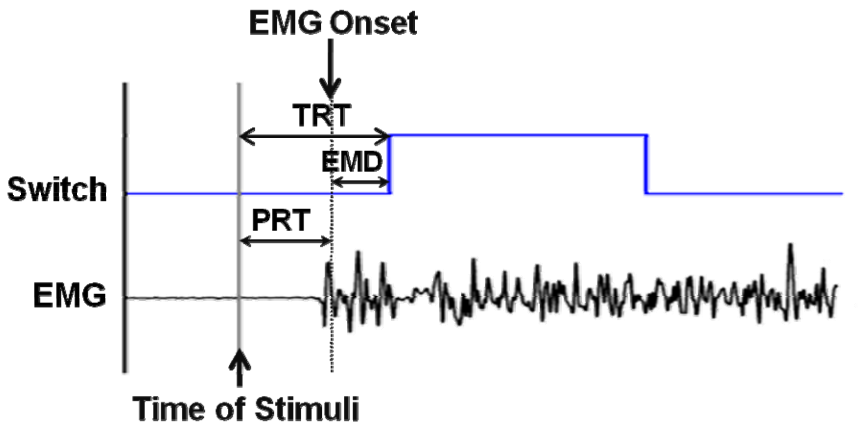


EMG signal and lasting for more than 10ms (McKinley & Pedotti, 1992). Movement onset was defined as any signal from the accelerometer that had a deviation of at least 2 SD that lasted for 5ms or above than the resting signal captured at 50ms before the stimulus. A sample of the raw signal is illustrated in Figure 8. PRT is the time lapse between the appearance of the stimulus and onset of EMG activities, while EMD is the time lapse between onset of EMG activities and force registration by the thumb switch or accelerometer.

3.4.6 Data analysis

The age, body weight, height, and body mass index (BMI) between groups were compared with one-way analysis of variance (ANOVA). The between-group difference in the mean values of PRT, EMD, and TRT to the three stimuli were analyzed by two-way analysis of covariance (ANCOVA) (Group x stimulus) with height taken as the covariate. When a significant main effect for group, stimulus or group by stimulus interaction was found, one-way ANCOVA with post hoc Bonferroni adjusted comparison were performed to determine specific differences. Significance level was set as 0.05 for all the tests.

Figure 8. Graphical illustration of the raw data of reaction time test.



TRT: Total reaction time, EMD: Electromechanical delay, PRT: Premotor reaction time

3.4.7 Results

3.4.7.1 Demographic data

Age, height, weight, BMI, and year of TKD experience for the subjects are shown in Table 4. Significant difference was found in age, height, and weight of the three groups. In view that body height has a strong correlation with nerve conduction velocity (Rivner, et al., 2001) which affects reaction time, the body height was therefore included as a covariate term in the statistical model.

3.4.7.2 Premotor reaction time

Significant interaction effects ($p<0.001$) for PRT were found in both RF and FPB. The follow up analysis showed significant group effect for PRT in both RF ($p<0.001$) and FPB ($p<0.001$) to audio stimulus, whereas statistical significance was found with general visual stimulus ($p<0.014$) in RF, and sport-specific stimulus ($p=0.003$) in FPB. Subsequent pair-wise comparisons revealed that professional TKD practitioners have significantly longer PRT to audio stimulus than amateur TKD practitioners (FPB: $p<0.01$; RF: $p<0.01$) and non-athletes (FPB: $p<0.001$; RF: $p<0.001$) (Tables 5 and 6). Professional TKD

Table 4. Demographic data of the three groups of subjects (Mean±SD)

		Professional	Amateur	Non-athletes
Age (years)		19±1.9	21±1.3	23±3.5
Gender (n)	Male	15	10	12
	Female	5	10	8
Height (cm)		181.0±7.23	164.3±10.09	169.2±9.59
Weight (kg)		67.1±8.74	56.3±8.52	60.2±9.50
BMI (kg/m^2)		20.4	20.8	20.9
TKD experience (years)		5.3±1.98	1.9±0.57	

Table 5. Mean (SD) of total reaction time, premotor reaction time, electromechanical delay and rheobase of rectus femoris for different stimulus.

	Stimulus	Professional	Amateur	Non-athletes
Premotor reaction time (ms)	Audio	217 (25.0)	145 (22.9)*	155 (23.3)*
	Visual	193 (21.4)	164 (16.8)#	181 (31.2)
	Sports-specific	250 (42.8)	255 (44.2)	268 (51.5)
Electromechanical delay (ms)	Audio	46 (31.7)	53 (23.5)	54 (24.7)
	Visual	48 (22.8)	51 (23.4)	56 (29.0)
	Sports-specific	56 (31.6)	60 (22.5)	65 (31.2)
Total reaction time (ms)	Audio	263 (38.4)	198 (28.4)#	208 (39.6)#
	Visual	238 (30.9)	214 (32.3)	237 (41.8)
	Sports-specific	306 (51.2)	315 (42.0)	332 (44.4)#
Rheobase (mA)		3.2 (0.68)	5.2 (1.47)#	5.7 (1.59)*

* Significantly different from professional TKD practitioners with $p<0.01$.

Significantly different from professional TKD practitioners with $p<0.05$

Table 6. Mean (SD) of total reaction time, premotor reaction time, electromechanical delay and rheobase of flexor pollicis brevis for different stimulus.

	Stimulus	Professional	Amateur	Non-athletes
Premotor reaction time (ms)	Audio	197 (18.8)	131 (23.7)*	150 (33.0)*
	Visual	181 (26.6)	159 (24.3)	159 (25.2)
	Sports-specific	228 (47.3)	243 (55.5)#	265 (44.9)#
Electromechanical delay (ms)	Audio	73 (32.4)	53 (16.3)#	60 (17.4)
	Visual	65 (18.1)	55 (13.9)	61 (15.9)
	Sports-specific	68 (24.0)	54 (18.7)#	59 (14.2)
Total reaction time (ms)	Audio	270 (33.4)	184 (21.4)*	210 (35.6)*
	Visual	246 (31.6)	214 (22.9)	222 (22.8)
	Sports-specific	296 (44.8)	297 (53.0)	324 (45.3)#
Rheobase (mA)		1.7 (0.32)	1.0 (0.27)*	0.9 (0.25)*

* Significantly different from professional TKD practitioners with $p<0.01$.

Significantly different from professional TKD practitioners with $p<0.05$

practitioners also have longer PRT to general visual stimulus (p=0.014) for RF than amateur TKD practitioners, but shorter PRT to sport-specific stimulus for FPB compared to amateur TKD practitioners (p=0.046) and non athletes (p=0.002) (Figure 9 and 10).

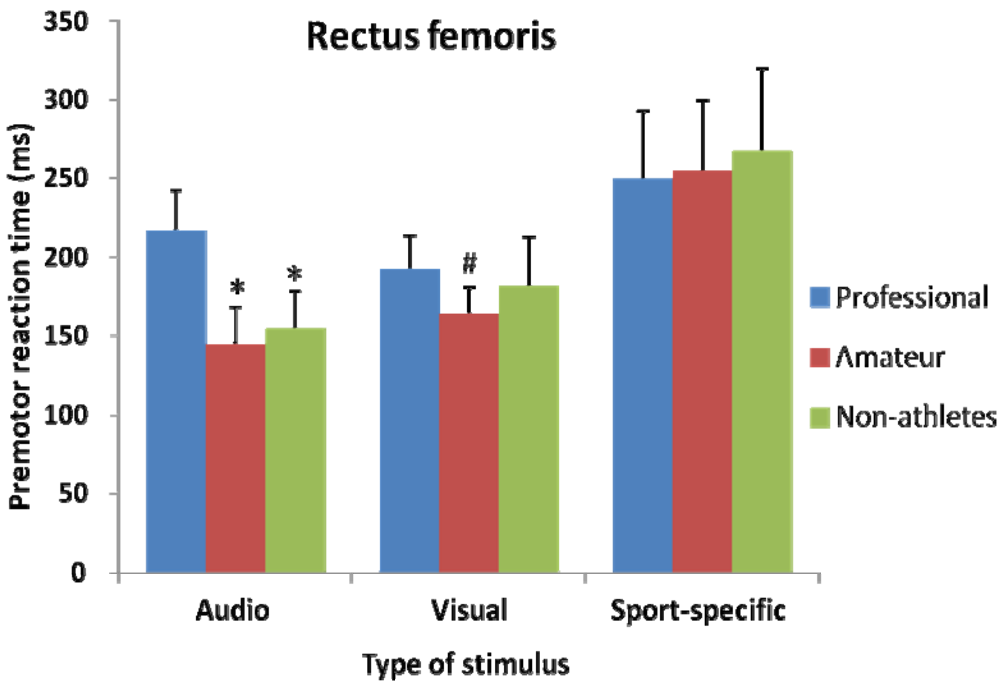
3.4.7.3 Electromechanical delay

There were no significant main effects for EMD of RF (Figure 11), while a group effect was found in FPB (Figure 12). One-way ANCOVA showed significant group effects in EMD with audio stimulus (p=0.035), and sport-specific stimulus (p=0.033) for FPB. The statistical results revealed that the amateurs have shorter EMD than the professionals in response to audio and sport-specific stimuli (Tables 5 and 6).

3.4.7.4 Total reaction time

Group by stimulus interactions were found in both RF and FPB for the TRT. Further analysis revealed a significant group effect in TRT of both RF (Figure 13) and FPB (Figure 14) with audio stimulus (RF: p<0.001; FPB: p<0.001), and sports-specific stimulus (RF: p=0.038; FPB: p=0.026). Post-hoc

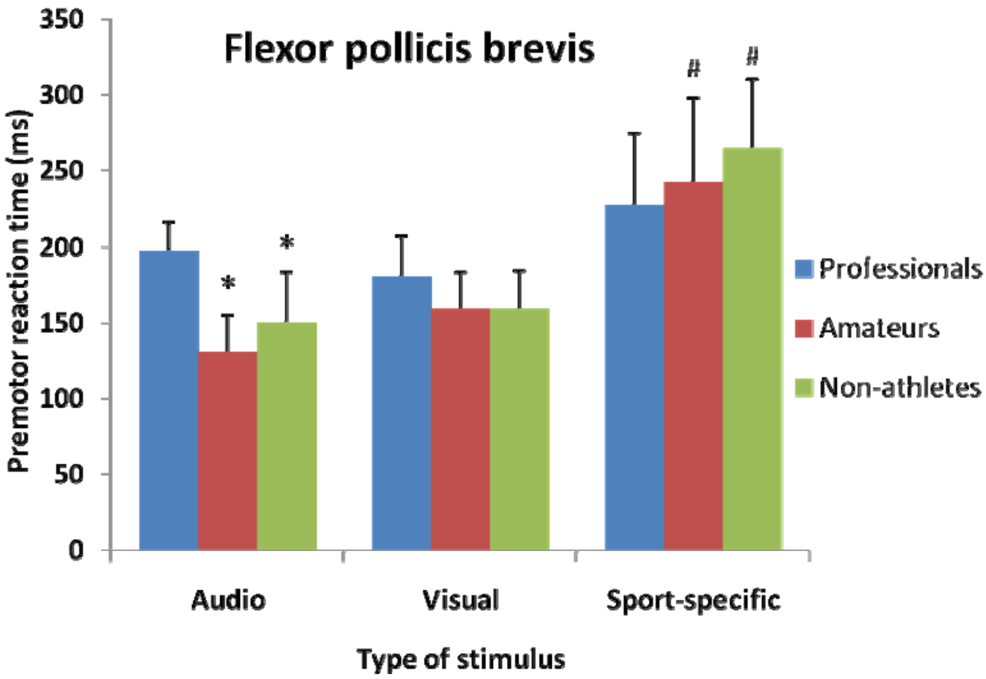
Figure 9. Mean and SD of premotor reaction time of rectus femoris to three type of stimulus.



* Significantly different from professional TKD practitioners with p<0.01.

Significantly different from professional TKD practitioners with p<0.05

Figure 10. Mean and SD of premotor reaction time of flexor pollicis brevis to three type of stimulus.



* Significantly different from professional TKD practitioners with p<0.01.

Significantly different from professional TKD practitioners with p<0.05

Figure 11. Mean and SD of electromechanical delay of rectus femoris to three type of stimulus.

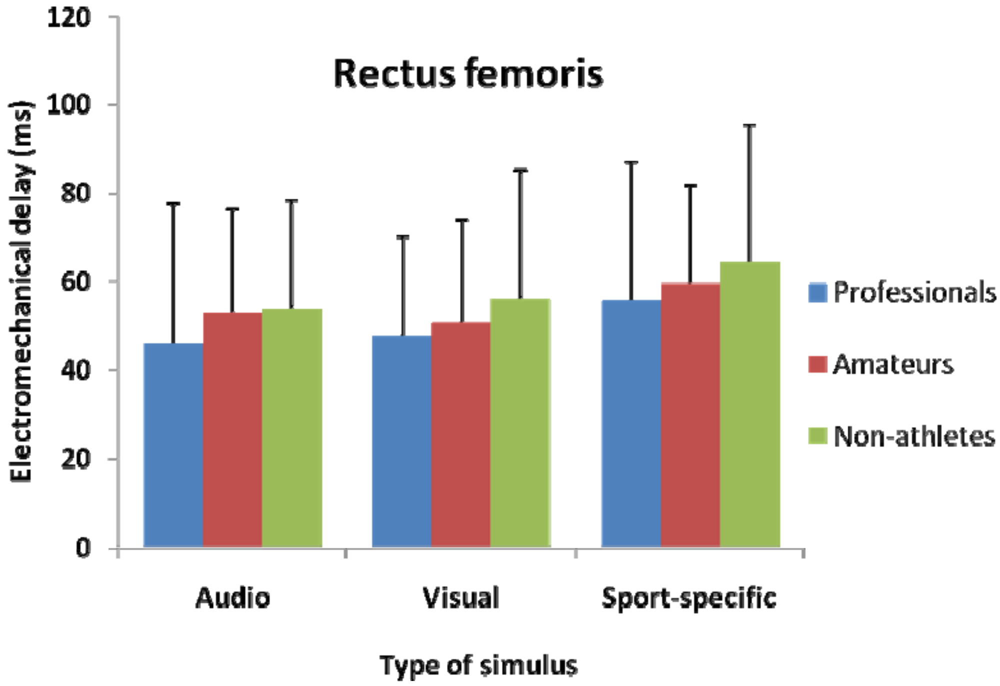
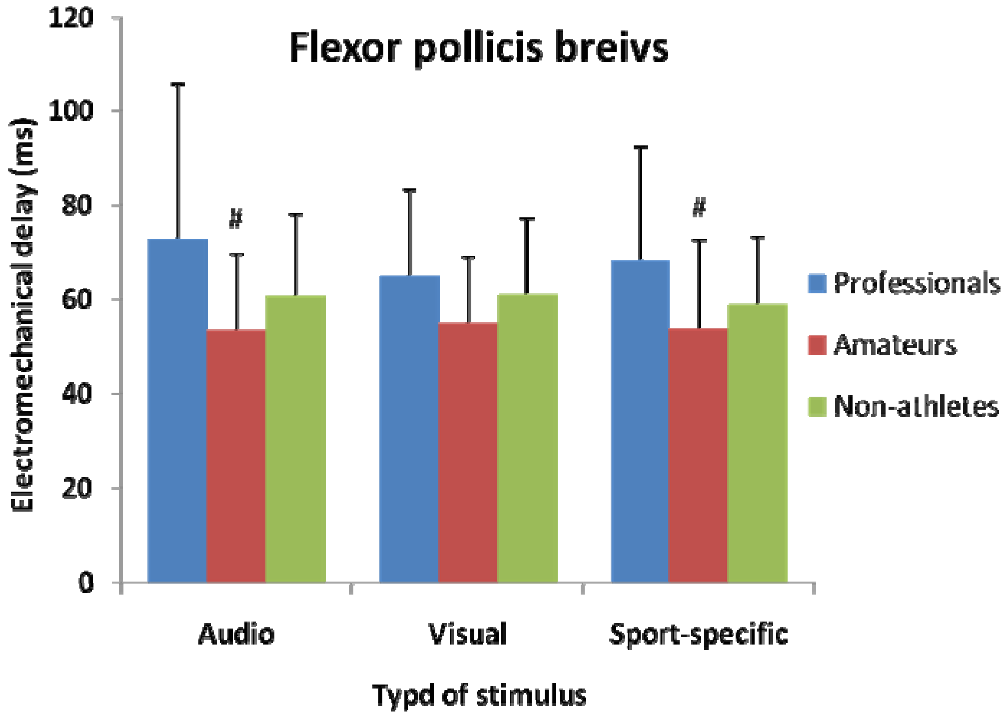
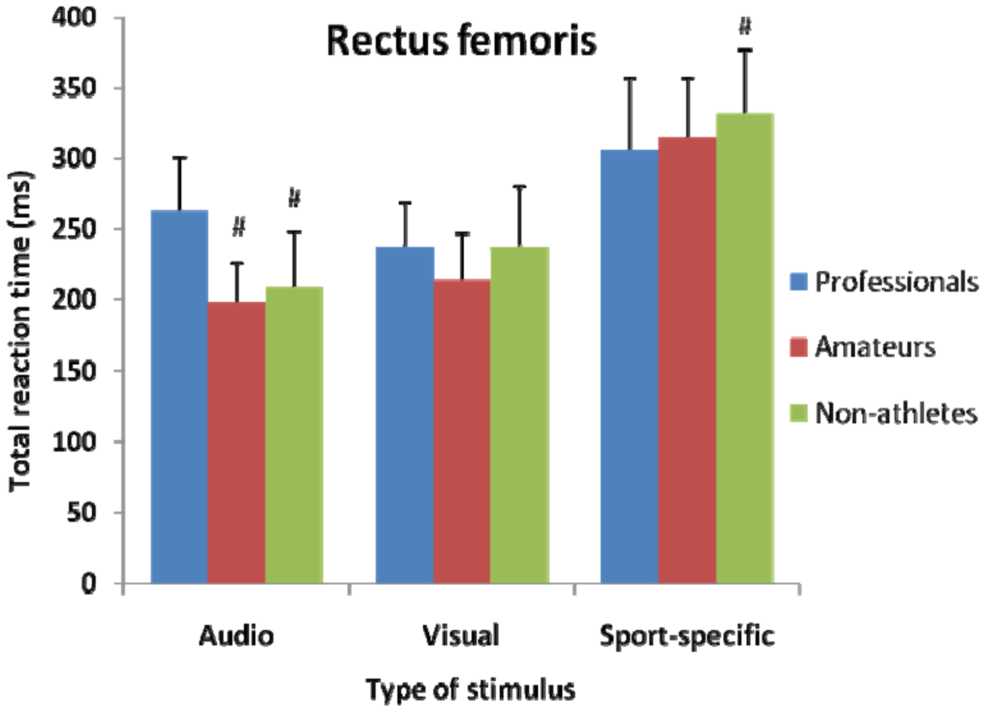


Figure 12. Meand and SD of electromechanical delay of flexor pollicis brevis to three type of stimulus.



Significantly different from professional TKD practitioners with $p<0.05$

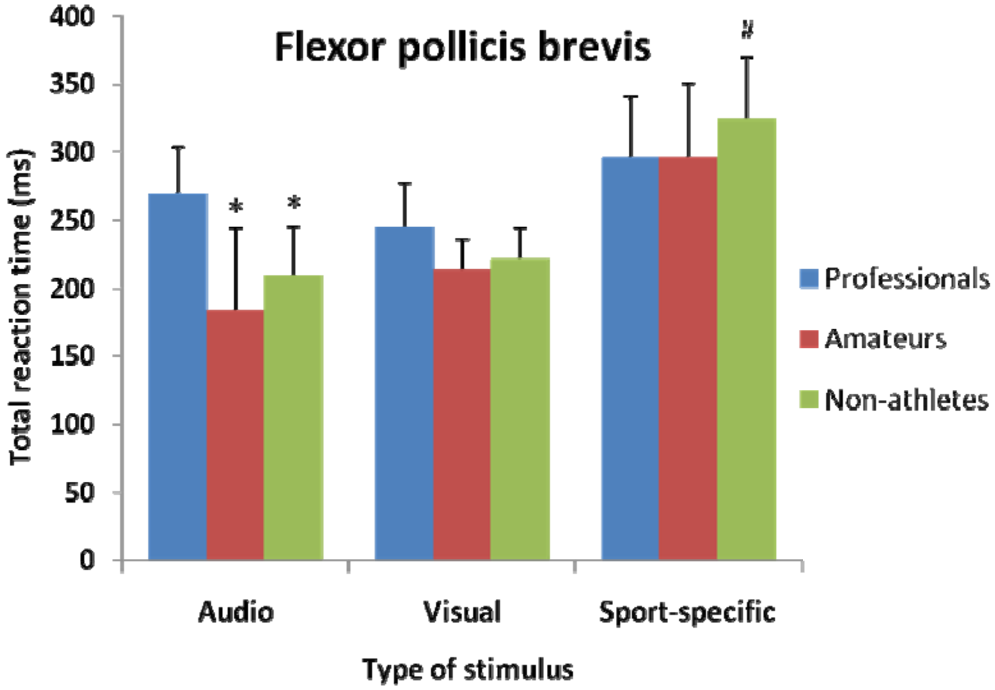
Figure 13. Mean and SD of total reaction time of rectus femoris to three type of stimulus



* Significantly different from professional TKD practitioners with $p<0.01$.

Significantly different from professional TKD practitioners with $p<0.05$

Figure 14. Mean and SD of total reaction time for flexor pollicis brevis to three type of stimulus.



* Significantly different from professional TKD practitioners with p<0.01.

\# Significantly different from professional TKD practitioners with p<0.05

pair-wise comparison showed that the professional practitioners have longer TRT than the amateurs, and non-athletes in response to audio stimulus, whereas both groups of TKD practitioners have shorter TRT than the non-athletes in response to sport-specific stimulus (Tables 5 and 6).

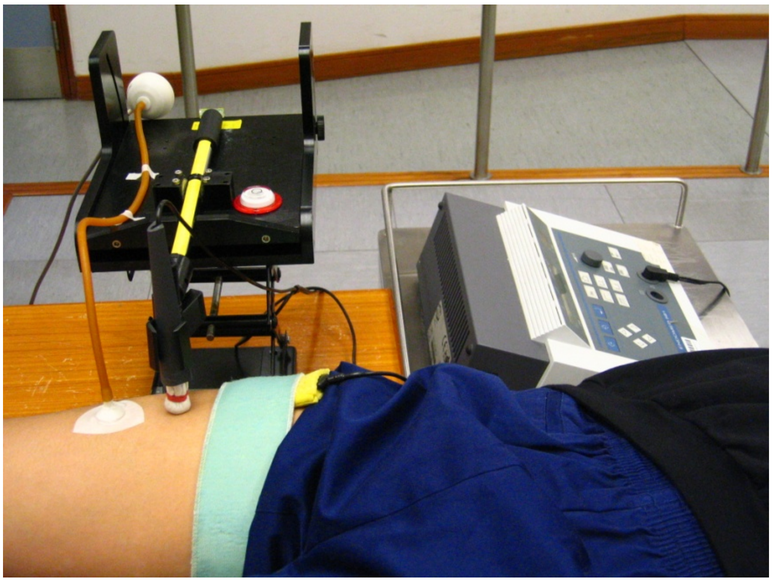
3.5 Strength duration test

3.5.1 Muscle stimulation

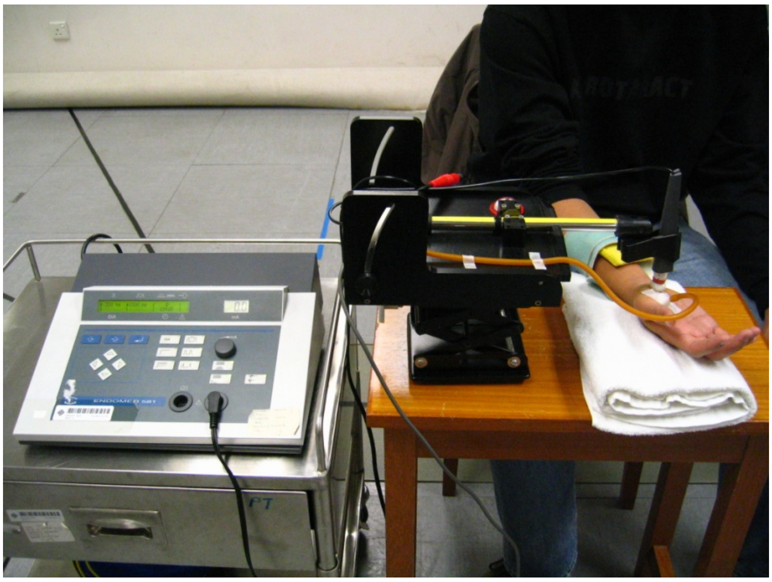
The neuromotor excitability of FPB and RF muscles was assessed by strength duration testing according to Robertson et al. (2006). FPB and RF were stimulated with a constant current stimulator (Endomed 581, Enraf-Nonius, Rotterdam, Netherlands). An active pointer electrode was applied on the motor point of the muscles being tested, and the pad dispersive electrode was placed at 4cm proximal to the active electrode. The active electrode was held with a stand which maintained the position and pressure during the test (Figure 15). The parameters of stimulation used were square-wave with inter-pulse duration of 1s (Robertson et al., 2006).

Figure 15. Positioning of the electrodes and pulse-transducer during strength duration test for two muscles

a. Rectus femoris



b. Flexor pollicis brevis



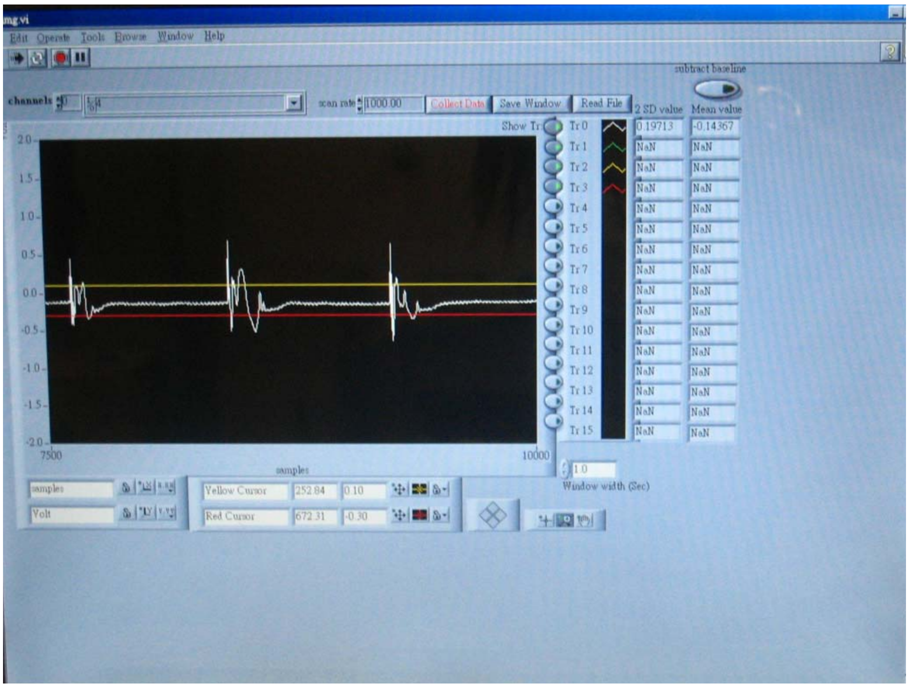
3.5.2 Detection of minimal muscle contraction

In the clinical setting, minimal muscle contraction has customarily been detected subjectively by visual observation or palpation by the examiner. In order to increase the objectivity in this study, the level of muscle contraction was quantified by mechanomyography (MMG) monitoring. An air-coupled pulse transducer head (Pulse Transducer Head 03040000, Cambridge Instrument Company Inc., Ossining, NY, USA) was attached to the muscles to measure the MMG signals (Wong et al., 2009) (Figure 15). The transducer was connected to an analog-digital converter with a sampling rate of 1000Hz (DAQPad-6020E, National Instrument, TX, USA) and the real time MMG signal could be shown on a computer screen positioned in front of the investigator (Figure 16).

3.5.3 Testing procedure

Before the test, 200ms of resting MMG signals were captured so as to establish the resting muscle activity level. The threshold of minimal detectable muscle contraction was defined as a signal with more than 2 SD higher than the mean resting MMG signal. Two reference lines indicating the threshold values and real-time MMG signal were displayed on the computer monitor throughout

Figure 16. An example of real-time MMG signals of the minimal muscle contraction. The red and yellow lines are the threshold of minimal muscle contraction, while the white line is the muscle activities.



the procedure.

To determine the threshold current, the amperage was slowly increased until the MMG signal exceeded the threshold values for 10 consecutive pulses. The threshold current intensity at pulse duration of 200, 100, 50, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1, and 0.05ms were recorded. The current required to elicit a muscle contraction at the pulse duration of 200ms was defined as the rheobase. Although only the threshold current at the longest pulse duration was used for analysis, the standard practice of testing 10-15 different pulse durations from 300 to 0.01ms for determining rheobase was followed (Alexander, 1974; Nelson & Hunt, 1981; Robertson et al., 2006). The reason for applying multiple pulse durations was to construct a complete strength duration curve, and the shape of the curve would be studied for any abnormality of the muscle electrical response.

3.5.4 Data analysis

The differences in rheobase of RF and FPB between groups were analyzed by one-way analysis of covariance (ANCOVA) with height taken as the covariate. Significant ANOVA results were further analyzed with post hoc Bonferroni test. Significance level was set as 0.05 for all the tests.

3.5.5 Results

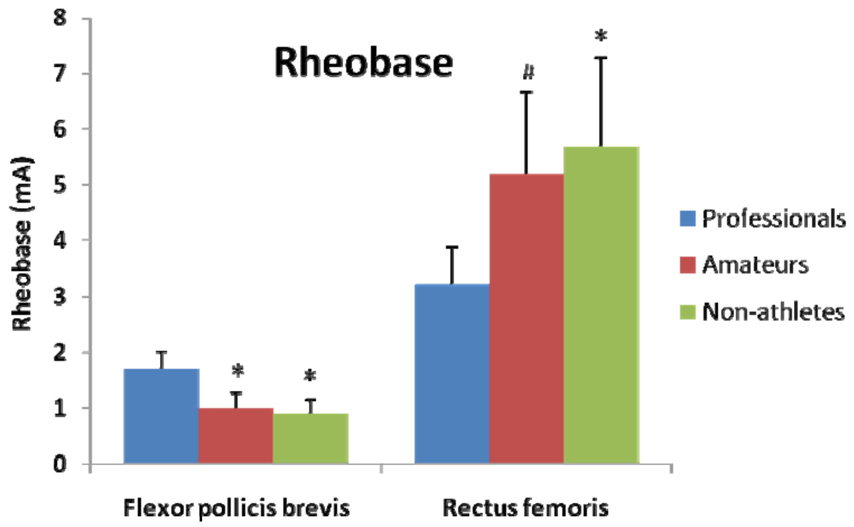
The rheobase was significantly higher for FPB, but lower for RF in the professional TKD practitioners than the amateur practitioners (FPB: $p<0.001$; RF: $p<0.014$), and non athletes (FPB: $p<0.001$; RF: $p<0.001$) (Figure 17; Tables 5 and 6).

3.6. Discussion

3.6.1a Reaction time to sport-specific stimulus

Results revealed a consistence trend of faster TRT and PRT to sport-specific visual stimulus in professional TKD practitioners than the amateurs and non-athletes, which is in line with the results found in karate athletes (Mori et al., 2002), and soccer players (Helsen & Starks, 1999). Mori et al. (2002) and Helsen and Starkes (1999) had compared the reaction time to light stimulus versus sport-specific visual stimulus between elite and novice athletes, and both reported that elite athletes had faster reactions to sport-specific stimuli. The faster reaction in well-trained athletes to sport-specific stimulus is widely postulated to be due to improvements in their sports related cognition (Abernethy, 1990; Mori et al., 2002).

Figure 17. Mean and SD of rheobase of rectus femoris and flexor pollicis brevis.



* Significantly different from professional TKD practitioners with $p<0.01$.

Significantly different from professional TKD practitioners with $p<0.05$

Mori et al. (2002) found that karate athletes could predict the attack motions of their opponents earlier than those novices karate practitioners when shown with pictures of attack forms. The authors suggested that faster reaction to sport-specific stimulus was due to better anticipatory skills in trained athletes.

Similarly, Abernethy (1990) reported that elite badminton players could predict the direction and force of badminton strokes from an earlier part of the opponents' movement in the films than novices. Helsen and Starkes (1999) also attributed the shorter response times in elite soccer athletes to their superior information processing ability such as more accurate interpretation of environmental cues, and faster selection of appropriate response in a simulated testing situation where the participants need to make a tactical decision with the ball trajectory as in a real game.

Since PRT reflects the time for perception and decision making (Schmidt & Lee, 1999), the present findings of shorter PRT in the professional TKD practitioners further support the argument that faster reaction in well-trained athletes is due to their superior sport-specific cognitive ability. Moreover, the present results revealed that the shortened reaction time to sport-specific stimulus was not limited to the muscles trained in TKD, the FPB which is not involved in TKD training, was also found to have faster reaction.

This is suggestive that the central processing is common in both the trained and untrained muscles.

Although the sport-specific stimulus was a static display of TKD pictures which did not involve decision making component, the shorter TRT and PRT in professional TKD practitioners would indicate that they have faster perceptual speed in discrimination of the sport-specific postures than the novices and non-athletes. Difference in visual search pattern between experts and novices TKD players as reported by Lee et al. (2010) could a possible cause for this finding. That study showed that TKD experts focus on the opponents' chest, while novices focused on the opponent's thigh. This suggests that professional TKD practitioners would be able to identify the body parts that provide most important kinematic information more effectively than the novices and react faster during TKD combat fighting.

3.6.1b Reaction time to audio and general visual stimulus

An interesting finding is that the professional TKD practitioners had longer TRT in responding to audio stimulation. Similar trends were shown in visual stimulus, although the differences were not significant. This finding is original and has never been reported.

Previous researchers had either found no difference in simple reaction time between professionals and novice sports practitioners or non-athletes (Helsen & Starkes, 1999; Kida et al., 2005; Mori et al., 2002; O'Donovan et al., 2006), or shorter reaction time in the professional practitioners (Ando et al., 2001; Nakamoto & Mori, 2008; Zwierko et al., 2010). By comparing the general visual reaction time with previous studies (Table 5), except for the study of O'Donovan et al. (2006) which reported same TRT in the non-athletes, the general visual reaction times of amateur TKD practitioners and non-athletes found in this study were consistently much shorter than the results reported by other researchers. While the visual reaction time of the professional TKD practitioners were similar or slightly longer than those previously reported.

Another possible reason for the slower reaction time to the difference in environmental factors during data collection may have contributed to this finding. Data collection for the amateur TKD practitioners and non-athletes were done in an air-conditioned laboratory at the Hong Kong Polytechnic University during summer time, while data collection of the professional TKD practitioners

Table 7. Review table of the general visual reaction time of different sports

Studies	Sports	Age	Type of response	General visual reaction time (ms)		
				Athletes	Novices	Non-athlete
Current study	Taekwondo	Professionals: 19±1.9 Amateurs: 21±1.3 Non-athletes: 23±3.5	Thumb switch press	246	214	222
Ando et al., 2001	Soccer	Intermediate: 21.5±1.4 Non-athlete: 22.8±0.8	Key press	243		246
Borysiuk &Bailey, 2007	Fencers	Advanced: 22.3 Novice: 14.8	Button press	200	244	
Helsen & Starkes, 1999	Soccer	Expert: 26.3 Intermediate: 22.5	Button press	Expert: 216 Intermediate: 221		
Kida et al., 2005	Baseball	Professional and intermediate baseball players: 21.6±2 Non-athletes: 22.9±1.7	Key press	241		245
Nakamoto & Mori, 2009	Basketball Baseball	All participants are university students	Key press	232	244	249
O'Donovan et al, 2006	Martial arts	Martial arts practitioners: 23.7±3.1 Non-athletes: 22.2±0.6	Key release	210		222
Zwierko et al, 2010	Volleyball	Division I players: 22.9±2.1 Non-athletes:21.9±3.9	Key release	241		287

was done in the Guangzhou Provincial Sports Training Center of China during winter time. Although the experimental set-up and positioning of the subjects were standardized, the room temperature in the Guangzhou Provincial Sport Training Center cannot be monitored and was lower than 25°C as in the air-conditioned laboratory. As many studies reported that decrease in body temperature may have adverse effects on the neuromuscular performance including increase in nerve conduction velocity and (Farell et al., 2011) and decrease in rate of force production (Cornwall, 1994), the lower room temperature during the data collection for the professional TKD practitioners may have affected the muscle performances.

The lifestyle of youths in Hong Kong could be an another contributing factor to the faster reaction time found in the amateurs and non-athletes. Playing video games is one of the most common leisure activities among youths in Hong Kong. In previous prevalence study by Lam et al. (2010), it was reported that around 75% of the people aged 9-13 years (n=611, mean age 10.5 years) played video games, and the duration was around 2 hours per week, whereas only around 10% of the youths of comparable age in Mainland China would engage in 1-2 hours of sedentary activities including playing video games. It has been published that video game players have faster reaction time than non-video game players (Castel et al., 2005; Dye et al., 2009), therefore the difference in life style between the professional TKD practitioners recruited from Mainland China and the amateur TKD practitioners and non-athletes recruited from Hong Kong could be one of the explanation for the significantly faster reaction to general stimulus found in amateurs and non-athletes. However, this is a hypothesis yet to be tested as to the life-style difference between the subjects in Hong Kong and Mainland China.

The summary of previous studies (Table 4) revealed that the general visual reaction time of the professional TKD subjects is about 10-20ms slower than that reported in other sports. Herpin et al. (2010), studying the sensorimotor specificities in balance control of fencers and pistol shooters, had found those athletes to have shifted their visual attention to the most relevant information, and relying more on vestibular and proprioceptive cues for balance control. Similarly, Paillard et al. (2006) reported that with improved sports skills, there would be decrease in the reliance on visual cues for postural control in soccer players. This phenomenon was suggested to be caused by the needs to observe the location of the ball and other players during soccer games, so that the soccer players would make use of other sensory input such as proprioception for balance control instead of visual input.

The phenomenon of decrease in visual attention for postural control also appears in TKD practitioners. In a recent study done by Leong et al. (2011), the balance performance of low-level TKD practitioners was compared with that of the able-bodied subjects. Their results showed that the TKD practitioners performed better in the eyes closed condition in the sensory organisation test and they also had faster postural correction in the drop test. The authors suggested that the TKD practitioners relied more on the vestibular and somatosensory input for maintaining balance.

A preliminary study done by Sinnett and Kingstone (2010) showed that the grunting of the tennis players during a tennis hit would have negative effect on the opponent's performance. It is common that TKD athletes shout before they attack or pretend to attack, therefore, focusing on the opponent's movement is extremely important during TKD combat fighting as the athletes need to differentiate real offensive movements from feint and look for opportunities for effective attacks. The professional practitioners may focus their visual or audio attention to the combat scene rather than those background audio-visual noises to reduce distractions. It is therefore possible that intensive TKD training would lead to shifting of attention to the most important information of the match and decrease the sensitivity towards irrelevant sensory inputs, such as flash lights and chanting from the spectators, or grunting from the opponent.

3.6.2 Electromechanical delay

TKD training includes intensive practice of kicking techniques and strength training, which leads to increase in lower limb muscle strength (Heller et al., 1998; Tsokovic et al., 2004). Since MVC is shown to correlate with EMD (Zhou, 1995), a shorter EMD in professional TKD practitioners would be expected.

The present results revealed a consistent trend of shorter EMD in TKD practitioners for all stimuli (Figure 10). The trend of shorter EMD of RF suggested that TKD training could facilitate a series of physiological processes during muscle contractions (Cavanagh & Komi, 1979), and shorten the time delay between initiation of muscle activity and force production (Zhou et al., 1995). Whether this is correlated to the increase in MVC of RF, and rate of force production as found in weight lifters, needs further investigation (Zhou, 1995).

The lack of a standardized movement during the EMD testing could be a factor causing the insignificant findings. During the test, the subjects were asked to kick with their dominant leg as strong and as quickly as possible in response to different stimuli with a standardized sitting position, but the force and speed of the kicking motion were not controlled. Since EMD is related to the rate of force development (Zhou, 1995), and EMD would decrease with increasing percentage of MVC (Yavuz et al., 2010; Zhou et al., 1995), the variation in kicking speed and force could be the cause for the large variability in EMD among subjects, and thus leading to the difference to be not significant.

The EMD of RF found in this study is longer than those reported by other researchers (Table 6). This could be due to difference in methodologies because EMD was measured by performing MVC in other studies while subjects in the present study were tested by kicking with the leg without loading. Since EMD changes with a negative relationship with the contraction level (Yavuz et al., 2010; Zhou et al., 1995), the lower contraction level used in this study could lead to longer EMD comparing to other studies.

For the EMD of FPB, those TKD practitioners were not different from the non-practitioners. This is in line with the findings of Ando et al. (2001) that soccer players and non-athletes were not different in EMD in the key-pressing response to visual stimuli. Moreover, the trend of difference in EMD between

Table 8. Review table of electromechanical delay

Studies	Subjects	Testing methods	Electromechanical delay (ms)		
			Athletes	Novices	Non-athletes
Current study	Professional TKD practitioners: 19 years Amateur TKD practitioners: 21years Non-athletes: 23years Taekwondo	Knee extension in response to light stimulus	48	51	56
Kubo et al., 2001	Non-athletes: 22.6years Soccer	Knee extension MVC performed as rapidly as possible			52.6
Zhou, 1995	Endurance athletes		43		
Zhou, 1995	Weight lifters Soccer	Knee extension MVC in response to light signal	34.9		38.1
Zhou et al., 1996	Non-athletes: 18.8years Basketball				38

groups was not affected by the type of stimulus. The trend of shorter EMD was only found in the large lower limb muscles of RF, but not in thumb muscles of FPB signifies that EMD is a physiological process unique for the muscles, and the effect of training is specific to the trained muscle group.

3.6.3a Neuromotor excitability in RF

The differences in rheobase between groups were directionally opposite in RF and FPB. The professional TKD practitioners had lower rheobase in RF, but higher rheobase in FPB comparing to the amateur TKD practitioners and non-athletes. The findings implied that the professional TKD practitioners have higher excitability in RF but lower excitability in FPB.

Neuromotor excitability depends on the Na^+/K^+ concentration gradient across the sacrolemma and T-tubular membrane of the muscles fibres which is regulated by the Na^+/K^+ pumps (Yerdelen et al., 2006). An increase in Na^+/K^+ pump concentration would lead to faster recovery of concentration gradient across the cell membranes and hence maintain excitability and contractibility during repeated contractions (Clausen, 1996; McKenna et al., 2008). In a review of the relationship between ionic pumping mechanism and skeletal muscle contractility, Clausen (2003) concluded that Na^+/K^+ pumps concentration could be facilitated by endurance training or strength training, which would lead to increase in neuromotor excitability, and this effect is restricted to the muscles being trained. Therefore, the present results have further supported the argument that training effects on neuromotor excitability is muscle-specific. However, whether the higher neuromotor excitability in TKD practitioner was due to changes in the physiology of Na^+/K^+ regulation warrants further investigation.

Higher neuromotor excitability would be beneficial for the athletes as it implies higher level of muscle arousal for performing quick and powerful movements. Besides, higher excitability is suggestive of better muscle contractility and fatigue resistance (Clausen, 1996). This could be an important factor for maintaining one's ability in performing powerful and effective kicks during TKD competitions.

The lack of difference in rheobase between amateur TKD practitioners and non-athletes implies that higher training intensity is needed to alter the neuromotor excitability. Two training sessions of 2-3 hours a week may not induce physiological changes in the muscle excitability in the amateur TKD practitioners. However, there is no reported study investigating the effective training protocol such as the optimal mode and intensity for training on improving neuromotor excitability, and these need to be further investigated.

3.6.3b Neuromotor excitability in FPB

No previous studies had shown that exercise training would lead to decrease in neuromotor excitability, but rather the opposite were reported (Evertsen et al., 1997; McKenna et al., 1993; Medbø et al., 2001). Moreover, no component of the TKD training is specific to the fine hand movements. Therefore, the lower rheobase in FPB found in professional TKD practitioners is less likely to be due to training effects. The reason for this phenomenon is not known, and the information obtained from the present study could not allow a scientific deduction of the reason. Therefore, further study on the physiology of the untrained muscles in these athletes is warranted.

3.7 Conclusion

This study showed that athletes receiving long-term intensive TKD training have faster PRT and TRT in recognition of sport-specific information in both trained and untrained muscles. Professional TKD practitioners also have better physiological performance in terms of shorter EMD and higher excitability in the large trained muscles. The professional TKD practitioners reacted slower than amateurs and non-athletes to non-sport specific stimuli. This finding suggested a decrease in sensitivity to irrelevant sensory inputs after long-term intensive TKD training.

Chapter 4 Grand discussion and conclusion

4.1 Training program of TKD and neuromotor control mechanisms

This study aimed to examine the neuromotor control mechanisms on different training levels of Taekwondo (TKD) practitioners. The temporal parameters of both cognitive and physiological components were measured and compared between TKD practitioners and non-athletes. The results showed that people who had received more than 3 years of intensive TKD training had shorter premotor reaction time (PRT), total reaction time (TRT) to the sport-specific stimulus, trend of shorter electromechanical delay (EMD), and higher muscle excitability than the amateur TKD practitioners who had 1-3 years of TKD experience and the non-athletes, when comparing the amateur practitioners and non-athletes, no difference was found in any of the parameters. This implied that long-term intensive TKD training may lead to improvement in cognitive and physiological abilities in the athletes, but low-level TKD training of less than 3 years would not lead to significant improvement in the neuromotor control mechanisms.

The difference in TRT is similar to the findings reported by Kida et al. (2005) in which high school students received two years of baseball practice had significantly shorter “Go/Nogo” reaction time compared to non-baseball players and no difference were found between non-athletes and students received one and two years of baseball practice. Kida et al. suggested that since there was no difference in reaction time in the beginning of the study and after 1 year of baseball practice, the shorter “Go/Nogo” reaction time is not innate. It is suggestive that the effects of sports training on reaction time may take two years to consolidate. Whether the lack of improvement after one or two years of sports practice is due to insufficient training intensity warrant further investigations.

Other than duration of TKD training, the intensity and components of training may have led to the difference in reaction time between the professionals and amateurs. The training program of the professional TKD practitioners included regular physical conditioning and strength training in addition to 5-6 sessions of TKD practice every week. The training program of the amateurs practitioners included a minor portion of stretching exercise and plyometric exercise to complement the TKD skill training. Other than the 2 -3 sessions of TKD practice, the training program does not include physical conditioning. According to a report on tennis training by Salonikidis and Zafeiridis (2008), plyometric training is superior to tennis drills to improve reaction time and maximum knee extension force in novice tennis players, but only tennis drills could improve 12-m sprint performance and the combined training could improve both aspects. Therefore, a comprehensive athletic training program would be important for the better performance of the TKD practitioners.

4.2 Training level of TKD and reaction time

The measured parameters were compared between trained and untrained muscles to examine whether the effects of training is movement specific. The results of PRT and TRT showed very similar trends in RF and FPB, whereas for the EMD and muscle excitability, the results showed different trends in the two muscles. The fundamental construct of PRT signifies the cognitive ability which included the time for perception of a signal and also the decision making processes (Schmidt & Lee, 1999), whereas EMD and muscle excitability are physiological mechanisms during muscle activations (Cavanagh & Komi, 1979; Yerdelen et al., 2006). These suggested that the effects of TKD training on cognitive components of the neuromotor control would be manifested in both trained and untrained muscles, while the training effects of the physiological components are specific only to the muscles actively involved in that sport. The present finding is also indicative that the perception and motor planning processes of the RF and FPB shared common pathways.

4.3 Training level of TKD in response to different types of stimuli

The results of this study are in line with previous studies which showed that effects of sport training are domain-specific (Abernethy, 1996; Helsen and Starkes, 1999; Kioumourtzoglou et al., 1998). Professional TKD athletes had faster reaction time to visual stimulation of an attack motion, but slower reaction time to audio and non-sport related visual stimuli than amateur practitioners and non-athletes in both trained and untrained muscles. This supported that athletes are able to detect sport-specific information faster than the non-athletes (Abernethy & Zawi, 2007; Helsen and Starkes, 1999).

As for the results of EMD, domain specificity was not shown. The professional TKD practitioners had shorter EMD in a large lower limb muscle (RF), but longer EMD in a small hand muscle (FPB) in all three types of stimuli. Since the series of neurophysiological processes involved in the excitation-contraction coupling should not be affected by the nature of stimulus, this finding is as expected.

4.4 Limitations of the study

This is a cross-sectional study and therefore the causal relationships between TKD training and the differences in reaction time, and neuromotor excitability found between TKD practitioners and non-athletes cannot be verified. A longitudinal study is needed to confirm the causal effects of sports training on the neuromotor control mechanism.

The sport-specific stimulus used in the present study was a photograph of a TKD athlete performing a kick preceded by a few photographs of the athlete in guarding positions. The series of photographs were shown in discrete images rather than a continuous video image of attacking movement. The PRT and TRT to sport-specific stimulus is consistently longer than the audio and visual stimuli in all groups, which indicated that certain level of decision making is involved in this sport-specific reaction time task. However, it could only reflect the ability of the TKD athletes to differentiate sport-specific static images, rather than a true reflection of the cognitive process during TKD combat fighting. In order to simulate a real situation, a video display of the attack action of a TKD athlete would be a more appropriate testing method.

The response movement of the reaction time test could not simulate TKD actions. Since the control subjects could not perform TKD kicks, and there would be variations in technique between subjects, the response movement was standardized as a knee extension movement in a sitting position in the lower limb reaction time test. However, this movement was not a natural reaction of the athlete in response to attack, and it may not truly reflect the athletes abilities if the training effects are movement specific.

Although the results of this study showed that TKD athletes have better performance in both cognitive and physiological components, the underlying mechanisms of the TKD training effects could not be verified in this study. The physiological or mechanical parameter were not examined, such as Na^+/K^+ pump mechanism which was proposed to be a determining factor for the muscle excitability (Clausen, 2003) and musculo-tendinous stiffness which was reported to be correlated to EMD (Grosset et al., 2009). These parameters would help to understand the underlying physiological changes of the TKD training and it needs to be further tested in future studies.

Low statistical power in some of the measured parameter was another limitation of this study. The power of 2-way ANCOVA of PRT and TRT were

1.00 and 0.99 respectively, while power of EMD analysis was 0.185 for FPB and 0.107 for RF. Regarding the post-hoc one-way ANCOVA, the power of PRT and TRT to audio stimulus was highest for both FPB and RF (0.969 to 1.00). The results of PRT and TRT to visual and sport-specific stimuli showed low to moderate power (0.181 to 0.76). While the power of the EMD results was moderate for FPB (0.544 to 0.646) and low for LL (0.211 to 0.262). Small sample size of this study may have limited the statistical power. Large between subject variations shown in EMD could be another contributing factor, and this could be improved by standardizing the speed or force of the response movement as mentioned in the discussion of Chapter 3.

Due to the difficulties in recruiting TKD athletes who would compete at international levels in Hong Kong, professional TKD practitioners were recruited from Mainland China. This may have reduced the homogeneity of the subjects in terms of their socio-economic background and societal environmental effects. The difference in environment during data collection between professional TKD practitioners and the other two groups may lead to increase in between group variations.

4.5 Implication of this study

The present study reflected a trend that TKD practitioners at higher training level would react faster to sport-specific stimulus, but slower to the non-specific stimulus than the TKD practitioners at lower training level or non-athletes. These findings imply that intensive TKD training may lead to faster response in sports-specific conditions, but decreased the reactivity to audio or visual signal in the other environment. The neurophysiology characteristics of the trained muscles as reflected by the EMD and muscle excitability may also be improved with 3 years of high intensity TKD practice.

The results of this study showed no difference in the reaction time and muscle excitability between the amateurs and non-athletes. Therefore, according to the present findings, neuromotor control would not be improved with 1-3 years of low-level TKD training.

The present results revealed that PRT occupied a large portion of the TRT, and this suggests that PRT is a more important determining factor of the neuromotor performance comparing with EMD. Previous studies have reported that elite athletes performed better in sport-specific reaction task, and this was thought to be related to the better knowledge of the game situation and perception, such as more accurate interpretation of the opponent's movement and other environmental cues by the athletes (Abernethy, 1996; Helsen & Starkes, 1999). These factors would enrich the athlete's sport-specific knowledge which may help to enhance the cognitive ability, thus improve the neuromotor performance. This study has used TKD as a model in view of its training involves high speed data processing and responses. The findings may also be applicable for sports of similar nature such as racket games or combat type of sports. For sports that do not involve constant information processing or reaction, such as swimming or running, the findings may not be generalized to these sports.

4.6 Clinical application

Both physical and cognitive aspects were more important to the TKD player's performance. However, the priority of each unique aspect in the training program may be different for TKD players at various training levels.

The major difference between two groups of TKD practitioners was that the training for the professionals had incorporated a much larger component of physical conditioning and strength whereas that for the amateurs focused more on the skill aspects. For the professional TKD practitioners who received intensive and comprehensive training, their sport cognition may be of higher importance to further improve their response towards the competition dynamics. Many of the research reports have stated that faster reaction time in athletes is related to cognitive abilities (Abernethy & Zawi, 2007; Kioumourtzoglou et al., 1998; Mori et al., 2002; Muller et al., 2010). Therefore, the training for the professional TKD players could incorporate more TKD combat and movement analysis of their opponents performance before competitions.

4.7 Suggestion for future studies

With the validation of the accelerometer as a portable and convenient tool for measuring reaction time, more study on the lower-limb reaction time shall be done to investigate the effects of sport training on different movements.

Although reaction time has been extensively studied in the athletic population, previous studies had mainly focused on the sport-specific cognitive function in athletes, which found that athletes could perceive, analyze and decide sport-specific information faster than non-athletes (Abernethy & Zawi, 2007; Helsen & Starks, 1999; Kioumourtzoglou et al., 1998; Mori et al., 2002; Muller et al., 2010). This study found that TKD athletes had better performance in both the cognitive and physiological components in terms of EMD and muscle excitability. The physiological and biomechanical factors that may affect EMD and muscle excitability such as MVC, musculo-tendinous stiffness, Na^+/K^+ regulations should be further investigated.

The finding that TKD athletes have slower reaction to general audio and visual signal is an interesting and unexpected finding. It may indicate a decrease in sensitivity to those signals after long-term intensive sports training. The cause and effects of this phenomenon and whether it is beneficial to the sports performance should be further investigated.

This is the first study which compared the neuromotor excitability by a non-invasive method of rheobase measurement, and the results showed that professional athletes had higher excitability than the amateurs and non-athletes. Since neuromotor excitability of the muscles were suggested to be related to muscle contractility (Clausen, 1996), fatigue resistance (McKenna et al, 2008), and neuromotor dysfunction (Kaczmarek et al., 2008), the relationship between neuromotor excitability and the risk of injury or competitive performance is worth further investigations.

4.8 Conclusion

This study has preliminarily demonstrated that athletes receiving long-term intensive TKD training have better sport-specific cognitive ability than the amateur TKD practitioners and non-athlete in both trained and untrained muscles. Professional TKD practitioners also have better physiological performance as reflected in higher muscle excitability and trends of shortening of EMD in the trained muscles. These signified that the levels of TKD skills are associated with the physiological reactive contractile function of the muscles that are intensively involved in the training.

References

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology* 93: 1318-1326.
2. Abernethy B. (1990). Anticipation in squash: differences in advance cue utilization between expert and novice players. *Journal of Sports Sciences* 8(1):17-34.
3. Abernethy B. (1996). Training the visual-perceptual skills of athletes insights for the study of motor expertise. *American Journal of Sports Medicine* 24:s89-92
4. Abernethy B, Zawi K. (2007). Pickup of essential kinematics underpins expert perception of movement patterns. *Journal of Motor Behaviour* 39(5):353-367.
5. Alexander J. (1974) Reproducibility of strength-duration curves. *Archives of Physical Medicine* 55(2):56-60.
6. Ando S, Kida N, Oda S. (2001). Central and peripheral visual reaction time of soccer players and nonathletes. *Perceptual and Motor Skills* 92:786-794.
7. Armstrong WJ, Mc Gregor SJ, Yaggie JA, Bailey JJ, Johnson SM, Goin AM, Kelly SR. (2010). Reliability of mechanomyography and triaxial accelerometry in the assessment of balance. *Journal of Electromyography and Kinesiology*

20:726-31.

8. Bland JM, Altman DG. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lance*t 1:307-10.

9. Bland JM, Altman DG. (1999). Measuring agreement in method comparison studies. *Statistical Methods in Medical Research* 8:135-150.

10. Borysiuk Z & Bailey R. (2007). Influence of stimuli type on electromyography (EMG) signal, reaction and movement time in novice and advance fencers. *Journal of Human Movement Studies* 52:65-79.

11. Brown L, Wagner G, Hug E, Erdmann E. (1986). Ouabaun binding and inotropy in acute potassium depletion in guinea pigs. *Cardiovascular Research* 20:286-293.

12. Brudnak MA, Bundero D, Van Hecke FM. (2002). Are the hardmartial arts, such as the Korean martial art, TaeKwon-Do, of benefit to senior citizens? *Medical Hypotheses* 59(4):485-491.

13. Castel AD, Pratt J, Drummond E. (2005). The effects of action video games experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica* 119(2):217-230.

14. CastielloU, Umilta C. (1992). Orienting of attention in volleyball players. *International Journal of Sport Psychology* 23(4):301-310.

15. Cavanagh PR, Komi PV. (1979). Electromechanical delay in human skeletal muscle under concentric and eccentric conditions. *European Journal of Applied Physiol*ogy 42(3):159-63.

16. Chen KY, Bassett Jr. DR. (2005). The technology of accelerometry-based activity monitors: current and future. *Medicine & Science in Sports & Exercise* 37:S490-500.

17. Christou EA, Rodriguez TM. (2008). Time but not force is transferred between ipsilateral upper and lower limbs. *Journal of Motor Behaviour* 40:186-189

18. Clausen T. (1996). The Na^{+}, K^{+} pump in skeletal muscles: quantification, regulation and functional significance. *Acta Physiologica Scandinavica* 156:227-235.

19. Clausen T. (2003). Na^{+}-K^{+} pump regulation and skeletal muscle contractility. *Physiological Reviews* 83(4):1269-1324.

20. Cornu C, Almeida Silveira MI, Goube F. (1997). Influence of plyometric training on the mechanical impedance of the human ankle joint. *European Journal of Applied Physiology* 76:282-288.

21. Cornwell MW. (1994). Effect of temperature on muscle force and rate of muscle force production in men and women. *Journal of Orthopaedic and Sports Physical Therapy* 20:74-80.

22. Cromwell RL, Meyers PM, Meyers PE, Newton RA. (2007). Tae Kwon Do: An effective exercise for improving balance and walking ability in older adults. *Journal of Gerontolog:Medical Sciences* 62A(6):641-646.

23. Dane S, Hazar F, Tan Ü. (2008). Correlation between eye-hand reaction time and power of various muscles in badminton players. *International Journal of Neuroscience* 118:349-354.

24. Dye MWG, Green CS, Bavelier D. (2009). The development of attention skills in action video game players. *Neuropsychologia* 47:1780-1789.

25. Everts ME and Clausen T. (1994). The excitation induced activation of the Na^{+}, K^{+} pump in rats skeletal muscle. *American Journal of Physiology-Cell Physiology* 266:C925-C934.

26. Evertsen F, Medbø JI, Jebens E, Nicolaysen K. (1997). Hard training for 5 mo increases Na^{+}-K^{+} pump concentration in skeletal muscles of cross-country skiers. *AmericanJournal of Physiology-Regulatory Integrative and Comparative Physiology* 272:R1471-R1424.

27. Falco C, Alvarez O, Castillo I, Estevan I, Martos J, Mugarra F, Iradi A. (2009). Infuluence of the distance in a roundhouse kick's exerution time and impact force in Taekwondo. *Jounal of Biomechanics* 42:242-248.

28. Farrel C, Kalmar JM, Pretorius T, Gardiner PF, Giesbrecht GG. (2011). Whole-body hypothermia has central and peripheral influences on elbow flexor performance. *Experimental Physiology* 96:528-538.

29. Fong SM, Ng GYF. (2010). The effect of Taekwondo training on balance and sensory performance in young adolescents. *The 7th Pan-Pacific Conference on Rehabilitation and 2010 Graduate Student Conference on Rehabilitation Sciences.* Hong Kong, China. P. 28.

30. Freriks B, Hermens H, Disselhorst-Klug C, Rau G. (1999) The recommendations for sensors and sensor placement procedures for surface electromyography. In: Hermens HJ, Freriks B, Merletti R, Stegeman D, Bolk J, Rau G, Disselhorst-Klug C, Hagg G, editors. European recommendations for surface electromyography: results of the SENIAM project. The Netherlands: Roessingh Research and Development, 1999:13-25.

31. Friedli WG, Meyer M. (1984). Strength-duration curve: a measure for assessing sensory deficit in peripheral neuropathy. *Journal of Neurology, Neurosurgery, and Psychiatry* 47:184-189.

32. Green H, Dahly A, Shoemaker K, Goreham C, Bombardier E, Ball-Burnett M. (1999). Serial effects of high-resistance and prolonged endurance training on Na^{+}-K^{+} pump concentration and enzymatic activities in human vastus lateralis.

Acta Physiologica Scandinavica 165:177-184.

33. Grosset, JF, Piscione D, Lambertz D, Perot C. (2009). Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. *European Journal of Applied Physiol*ogy 105(1):131-9.
34. Gilmore KL, Meyers JE. (1983). Using surface electromyography in physiotherapy research. *Australian Journal of Physiotherapy*, 29 (1), 3-9.
35. Hakkinen K, Alen M, Komi PV. (1985) Changes in isometric force and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscles during strength training and detraining. *Acta Physiologica Scandinavica* 125:573-585.
36. Hakkinen K, Komi PV. (1983). Changes in neuromuscular performance in voluntary and reflex contraction during strength training in man. *International Journal of Sports Medicine* 4:282-288.
37. Harmenberg J, Ceci R Barvestad P, Hjerpe K, Nystrom J. (1991). Comparison of different tests of fencing performance. *International Journal of Sports Medicine* 12:573-376.
38. Heller J, Peri T, Dlouha R, Kohlikova E, Melichna J, Vakova H. (1998). Physiological profiles of male and female TKD black belt. *Journal of Sports Science* 16**:**243-249.

39. Helsen WF & Starks JL. (1999) A multidimensional approach to skilled perception and performance in sport. *Applied Cognitive Psychology* 13:1-27.

40. Henriksen M, Lund H, Moe-Nilssen R, Bliddal H, Danneskio-Samsoe B. (2004). Test-retest reliability of trunk accelerometric gait analysis. *Gait & Posture* 19:288-297.

41. Herpin G, Gauchard GC, Lion A, Collet P, Keller D, Perrin PP. (2010). Sensorimotor specificities in balance control of expert fencers and pistol shooters. *Journal Electromyography and Kinesiology 20*:162-169.

42. Irnich W. (2010). The terms “chronaxie” and “rheobase” are 100 years old. *Pacing and Clinical Electrophysiology* 33(4):491-6.

43. Kaczmarek K, Wysokinska A, Zytkowski A. (2008). Evaluation of vastus medialis excitability in children with lateral patellar instability. *Ortopedia, traumatologia, rehabilitacja* 10(6):583-592.

44. Kamen G, Kroll W, Clarkson PM, Zigon ST. (1981). Fractioned reaction time in power-trained and endurance-trained athletes under conditions of fatiguing isometric exercise. *Journal of Motor Behaviour* 13(2):117-129.

45. Kazemi M, Waalen J, Morgan C, White AR. (2006). A profile of Olympic taekwondo competitors. *Journal of Sports Science and Medicine* CSSI:114-121.

46. Kida N, Oda S, Matsumura M. (2005). Intensive baseball practice improves the Go/Nogo reaction time, but not the simple reaction time. *Cognitive Brain Research* 22:257-264.

47. Kioumourtzoglou E, Kourtessis T, Michalopoulou M, Derri V. (1998). Difference in several perceptual abilities between experts and novices in basketball, volleyball and water-polo. *Perceptual and Motor Skills* 86:899-912.

48. Kioumourtzoglou E, Michalopoulou M, Tzetzis G, Kourtessis T. (2000) Ability profile of the elite volleyball player. *Perceptual and Motor Skills* 90:757-770.

49. Krishnan AV, Kiernan MC. (2005). Altered nerve excitability properties in established diabetic neuropathy. *Brain* 128:1178-1187.

50. Kubo K, Kanehisa H, Ito M, Fukunaga T. (2001). Effects of isometric training on the elasticity of human tendon structures in vivo. *Journal of Applied Physiol*ogy 91(1):26-32.

51. Lam JW, Sit CH, Cerin D. (2010). Physical activity and sedentary behaviours in Hong Kong Primary school children: Prevalence and gender differences. *Preventive Medicine* 51:96-97.

52. Lee HK, Cho SP, You JH, Lee KY. (2007). The concurrent validity of the body center of mass in accelerometric measurement. *Proceedings of the 29th Annual International conference of The IEEE EMBS.* Lyon, France. P.23-26.

53. Lee JW, Kin SJ, Song Y. (2010). Visual search patterns and reaction movement in Taekwondo according to expertise. *Journal of Sports & Exercise Psychology,* 32:S99-S100.

54. Leong HT, Fu SN, Ng GYF, Tsang WWN. (2011). Low-level Taekwondo practitioners have better somatosensory organisation in standing balance than sedentary people. European Journal of Applied Physiology (Article in Press).

55. L'Hermette M, Savatier X, Baudry L, Tourny-Chollet C, Dujardin F. (2008). A new portable bevice for assessing locomotor. *International Journal of Sports Medicine*, 29:322-26.

56. Lieber RL. (2002). Skeletal Muscle Structure, function & plasticity: The physiological basic of rehabilitation. Philadelphia: Lippincott Williams& Wilkins.

57. Lidor R, Daniel S. (1998). An exploratory study of perceptual-motor abilities of women: novice and skilled players of team handball. *Perceptual and Motor Skills* 86:279-288.

58. Lord S, Rochester L, Baker K, Nieuwboer A. (2008). Concurrent validity of accelerometry to measure gait in Parkinsons Disease. *Gait & Posture* 27:357-9.

59. Lundy-Ekman L. (2007). Neuroscience: fundamentals for rehabilitation. St.

Louis, Mo: Saunders Elsevier.

60. Maclntosh BR, Gardiner PF, McComas AJ. (2006). Skeletal muscle: form and function. 2nd ed. Champaign Champaign, IL: *Human Kinetics.*

61. McGinley JL, Baker R, Wolfe R, Morris ME. (2009). The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait & Posture* 29:360-9.

62. McKenna MJ, Bangsno J, Renaud JM. (2008). Muscle K+, Na+, and Cl+ disturbances and $Na^{+}K^{+}$ pump inactivation implications for fatigue. *Journal of Applied Physiol*ogy 104:288-295.

63. McKenna MJ, Schmidt TA, Hagreaves M, Cameron L, Skinner SL, Kjeldsen K. (1993). Sprint training increases human skeletal-muscle Na^{+}-K^{+}-ATPase concentration and improves K^{+} regulation. *Journal of Applied Physiol*ogy 75:173-180.

64. McKinley PA, Pedotti A. (1992) Motor strategies in landing from a jump: the role of skill in task execution. *Experimental Brain Research* 90(2):427-40.

65. Meamarbashi A, Hossaini SRA. (2010). Application of novel inertial technique to compare the kinematics and kinetics of the legs in the soccer instep kick. *Journal of Human Kinetic*s 23:3-12.

66. Medbø JI, Jebens E, Vikne H, Refsnes PE, Gramvik P. (2001). Effect of

strenuous strength training on the Na-K pump concentration in skeletal muscle of well-trained men. *European Journal of Applied Physiol*ogy 84:148-154.

67. Moe-Nilssen R. (1998). Test-restest reliability of trunk accelerometry during standing and walking. *Archives of Physical Medicine and Rehabilitation* 79:1377-85.
68. Mori S, Ohtani Y, Imanaka K. (2002). Reaction times and anticipatory skills of karate athletes. *Human Movement Science* 21:213-230.
69. Muller S, Abernethy B, Eld M, McBean R, Roses M. (2010). Expertise and the spatio-temporal characteristics of anticipatory information pick-up from complex movement patterns. *Perception* 39(6):745-760.
70. Nakamoto H., Mori S. (2008). Sport-specific decision-making in a Go/Nogo reaction task: difference among nonathletes and baseball and basketball players. *Perceptual Motor Skills* 106:163-170
71. Nelson RM, Hunt GC. (1981). Strength-duration curve: intrarater and interrater reliability. *Physical Therapy* 61(6):894-897.
72. Ng GY. (2005). Patellar taping does not affect the onset of activities of vastus medialis obliquus and vastus lateralis before and after muscle fatigue. *American Journal of Physical Medicine and Rehabilitation* 84:106-111.
73. Nielsen OB, Clausen T. (1994). The significance of active Na+ and K+

transport for the maintenance of contractility in rat skeletal-muscle. *Journal of Physiology*-London 477P:P62.

74. O'Donovan O, Cheung, J, CatleyM, McGregor AH, Strutton PH. (2006). An investifation of leg and trunk strength and reaction times of hart-style martial arts practitioners. *Journal of Sports Sciences and Medicine* CSSI:5-12.

75. O'Sullivan D, Chung C, Lee K, Kim H, Kang S, Kim T, Shin I. (2009). Measurement and comparison of Taekwondo and Yongmudo turning kick impact forec for two target heights. *Journal of Sports Sciences and Medicine* 8(CSSI III): 13-16.

76. Paillard T, Noe F, Riviere T, Marion V, Montoya R, Dupui P. (2006). Postural performance and strategy in the unipedal stance of soccer players at difference levels of competition. *Journal of Athletic Training* 41(2):172-176.

77. Park YK, Park YH & Gerrard J. (1989). Tae Kwon Do: the ultimate reference guide to the world's most popular martial art. London:Ward Lock; 1989.

78. Pedzich W, Mastalerz A, Urbanki C. (2006). The comparison of the dynamics of selected leg strokes in taekwondo WTF. *Acta Bioengineering and Biomechanics* 8:1-8.

79. Pieter W, Taaffe D, Troxel R, Heijmans J. (1989). Isokinetic peak torque of the quadriceps and hamstrings of college age Taekwondo athletes. *Journal of*

Human Movement Studies 16:17-25.

80. Polk JD, Psutka SP, Demes B. (2005). Sampling frequencies and measurement error for linear and temporal gait parameters in primate locomotion. *Journal of Human Evolution* 49:665-79.

81. Pomeroy VM, Evans E, Richards JD. (2006). Agreement between an electrogoniometer and motion analysis system measuring angular velocity of the knee during walking after stroke. *Physiotherapy*, 92:159-65.

82. Portney LG, Walkins MP. (2009). Foundation of clinical research: application to practice. 3rd ed. Upper Saddle River: Pearson/Prentice Hall; 2009.

83. Rivner, MH, Swift TT, Malik K. (2001). Influence of age and height on nerve conduction. *Muscle and Nerv,* 24:1134-1141.

84. Robertson V, Ward A, Low J, Reed A. (2006) Electrotherapy Explained Principles and Practice. Edinburgh, NY: Elsevier Butterworth Heinemann.

85. Salonikidis K, Zafeiridis A. (2008) The effects of plyometric, tennis-frills, and combined training on reaction, lateral and linear speed, power, and strength in novices tennis players. *J Strength Cond Res*, 22:182-191.

86. Schmidt RA, Lee TD. (1999) Motor control and learning: a behavioral emphasis. Champaign, IL: *Human Kinetics.*

87. Schmidt RA, Wrisberg CA. (2004) Motor learning and performance. Champaign, IL: Human Kinetics.

88. Shinkai H, Nunome, H, Isokawa M, Ikegami, Y. (2009). Ball impact dynamics of instep soccer kicking. *Medicine and Science in Sports and Exercise* 41:889-897.

89. Sinnett S, Kingstone A. (2010). A preliminary investigation regarding the effect of tennis grunting: Does white noise during a tennis shot have a negative impact on shot perception? *PLoSOne* 5(10):e13148.

90. Song KY, An JD. (2004). Premotor and motor reaction time of educable mentally retarded youths in a taekwondo program. *Perceptual and Motor Skills* 99:711-723.

91. Toudor-Locke C, Ainsworth BE, Adair LS, Du S, Popkin BM. (2003). Physical activity and inactivity in Chinese school-aged youth: the China Health and Nutrition Survey. *International Journal of Obesity* 27:1093-1099.

92. Trost SG, Mciver KL, Pate RR. (2005). Conducting accelerometer–based activity assessments in field-based research. *Medicine & Science in Sports & Exercise* 37:S531-4.

93. Tsokovic NN, Blessing D, Williford HN. (2004). The effects of experience and gender on cardiovascular and metabolic responses with dynamic Tae kwon do exercise. *Journal of Strength and Conditioning Research* 16(2):278-285.

94. Udo H, Otani T, Udo A, Yoshinaga F. (2000) An electromyographic study of two different types of ballpoint pens-investigation of a one hour writing operation. *Industrial Health* 38:47-56.

95. Van Hees VT, Slootmaker SM, Groot GD, Van Mechelen W, Van Lummel RC. (2009). Reproducibility of triaxial seismic accelerometer (DynaPort). *Medicne & Science in Sports & Exercise* 41:810-7.

96. Webster KE, Wittwer JE, Feller WJ. (2005). Validity of GAITRite walkway system for the measurement of averaged and individual step parameters of gait. *Gait & Posture*, 22:317-21.

97. Whitley JD, Montano L. (1992). Relation between reaction time and movement time in college wrestlers. *Perceptual and Motor Skills* 74:171-176.

98. Williams LRT, Walmsley A. (2000) Response timeing and muscular coordination in fencing: a comparison of elite and novice fencers. *Journal of Science and Medicine in Sport* 3(4):460-475.

99. Wong YM, Chan ST, Tang KW, Ng GYF. (2009). Two modes of weight training programs and patellar stabilization. *Journal of Athletic Training* 44(3):264-271.

100. Yavuz SU, Sendemir-Urkmez A, Turker KS. (2010). Effect of gender, age, fatigue and contraction level on electromechanical delay. *Clinical Neurophysiology* 122:1700-1706.

101. Yerdelen D, Uysal, H. Koc F, Sarica Y. (2006) Effects of sex and age on strength–duration properties. *Clinical Neurophysiology* 117:2069-2072.

102. Zhang JG, Ishikawa-Takata K, Yamazaki H, Morita T, Ohta T. (2008). Postural stability and physical performance in social dancers. *Gait & Posture* 27:697-701

103. Zhou S. (1995). Electromechanical delay in weight lifters and endurance trained athletes. *XVth Congress of the International Society of Biomechanics*. Jyvaskyla, Finland. P. 1036-1037.

104. Zhou s, Lawson DL, Morrison WE, Fairwater I. (1995). Electromechanical delay in isometric muscle contractions evoked by voluntary, reflex and electrical stimulation. *European Journal of Applied Physiol*ogy 70:138-145.

105. Zhou S, Mckenna MJ, Lawson DL, Morrison WE, Fairwater I. (1996). Effects of fatigue and sprint training on electromechanical delay of knee extensor muscles. *European Journal of Applied Physiol*ogy 72:410-416.

106. Zwierko T, Osinski W, Lubinski W, Czepita D, Florkiewicz B. (2010). Speed of visual semsorimotor processes and conductivity of visual pathway in volleyball players. *Journal of Human Kinetics* 23:21-27.

Appendix I

Ethical approval by the Human Ethics Sub-committee of the Hong Kong Polytechnic University in Chapter 2

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

MEMO

To : NG Yin Fat, Department of Rehabilitation Sciences
From : YIP Kam Shing, Chairman, Faculty Research Committee, Faculty of Health & Social Sciences

Ethical Review of Research Project Involving Human Subjects

I write to inform you that approval has been given to your application for human subjects ethics review of the following research project for a period from 09/05/2011 to 30/06/2011:

Project Title : Comparison between accelerometer and 3D motion analyzing system in detecting movement

Department : Department of Rehabilitation Sciences

Principal Investigator : NG Yin Fat

Please note that you will be held responsible for the ethical approval granted for the project and the ethical conduct of the research personnel involved in the project. In the case the Co-PI has also obtained ethical approval for the project, the Co-PI will also assume the responsibility in respect of the ethical approval (in relation to the areas of expertise of respective Co-PI in accordance with the stipulations given by the approving authority).

You are responsible for informing the Faculty Research Committee Faculty of Health & Social Sciences in advance of any changes in the research proposal or procedures which may affect the validity of this ethical approval.

You will receive separate notification should you be required to obtain fresh approval.

YIP Kam Shing
Chairman
Faculty Research Committee
Faculty of Health & Social Sciences

Appendix II

Informed written consent form sample in Chapter 2

The Hong Kong Polytechnic University
Department of Rehabilitation Sciences
Research Project Informed Consent Form

Project title: Comparison between accelerometer and 3D motion analyzing system in detecting movement

Principal investigator: Gabriel NG, PT PhD, Professor & Associate Head, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University

Student investigator: Polly CHUNG, BSc (Hon) PT, Graduate student, Department of Rehabilitation Sciences, The Hong Kong polytechnic University

Project information:

The purpose of this study is to investigate the agreement between accelerometer and Vicon movement analysis system in measuring movement onset timing.

This study is to measure the audio motor response timing of the leg. An accelerometer and a reflective marker will be attached to the shin to detect the leg movement. Subjects will need to sit in front of the computer and kick with the leg upon hearing certain signal.

This study will take place at a laboratory in The Hong Kong Polytechnic University. The above procedures do not have any known risk and you shall not have any pain sensation. Your involvement will not be of direct benefit to you. However, findings of this study will be useful in the design of training and assessment protocols for the athletes so that their levels of skill can be further enhanced and the rate of injury be reduced.

Consent:

I, ____________________________ have been explained the details of this study. I voluntarily consent to participate in this study. I understand that I can withdraw from this study at any time without giving reasons, and my withdrawal will not lead to any punishment or prejudice against me. I am aware of any potential risk in joining this study. I also understand that my personal information will not be disclosed to people who are not related to this study and my name or photograph will not appear on any publications resulted from this study.

I can contact the investigator, Polly Chung, at telephone 27664451 for any questions about this study. If I have complaints related to the investigator(s), I can contact Mrs. Michelle Leung, secretary of Departmental Research Committee, at 2766-5397. I know I will be given a signed copy of this consent form.

Signature (subject): Date:

Signature (witness): Date:

Appendix III

Raw data of study in chapter 2

Accelerometer measurement

Subjects	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
1	214	195	130	186	171
2	199	249	275	293	229
3	180	211	199	180	163
4	230	181	178	183	210
5	291	273	255	234	309
6	277	263	259	223	250
7	156	148	152	193	133
8	214	233	275	259	243
9	200	121	182	128	170
10	208	197	210	264	199
11	119	108	156	107	104
12	245	219	220	239	205

VICON measurement

Subjects	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
1	254	220	171	197	131
2	165	236	249	271	221
3	177	212	204	185	167
4	195	155	140	136	173
5	261	212	194	181	276
6	215	186	232	193	178
7	150	157	145	131	120
8	198	220	278	270	227
9	201	144	119	146	189
10	244	211	205	274	215
11	154	138	189	149	136
12	269	233	245	254	217

Appendix IV

Ethical approval by the Human Ethics Sub-committee of the Hong Kong Polytechnic University in Chapter 3

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

MEMO

To : NG Yin Fat, Department of Rehabilitation Sciences
From : YIP Kam Shing, Chairman, Faculty Research Committee, Faculty of Health & Social Sciences

Ethical Review of Research Project Involving Human Subjects

I write to inform you that approval has been given to your application for human subjects ethics review of the following research project for a period from 26/04/2011 to 01/06/2011:

Project Title : Effects of Taekwondo Training on Neuromotor Control Mechanism

Department : Department of Rehabilitation Sciences

Principal Investigator : NG Yin Fat

Please note that you will be held responsible for the ethical approval granted for the project and the ethical conduct of the research personnel involved in the project. In the case the Co-PI has also obtained ethical approval for the project, the Co-PI will also assume the responsibility in respect of the ethical approval (in relation to the areas of expertise of respective Co-PI in accordance with the stipulations given by the approving authority).

You are responsible for informing the Faculty Research Committee Faculty of Health & Social Sciences in advance of any changes in the research proposal or procedures which may affect the validity of this ethical approval.

You will receive separate notification should you be required to obtain fresh approval.

YIP Kam Shing
Chairman
Faculty Research Committee
Faculty of Health & Social Sciences

Appendix V

Informed written consent form sample in Chapter 3 (English version)

The Hong Kong Polytechnic University
Department of Rehabilitation Sciences
Research Project Informed Consent Form

Project title: Effects of Taekwondo training on neuromotor control mechanism

Principal investigator: Gabriel NG, PT PhD, Professor & Associate Head, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University

Student investigator: Polly CHUNG, BSc (Hon) PT, Graduate student, Department of Rehabilitation Sciences, The Hong Kong polytechnic University

Project information:

The purpose of this study is to measure the muscle excitability, reflex timing and balance performance in high-level Taekwondo (TKD) practitioners and compare them with people not involved in this sport.

Muscle excitability will be measured with electrical stimulation on the muscles of your dominant arm and leg. The operator will use a stimulating probe to find the best stimulating points on the muscles and then apply different levels of current to elicit contraction of the muscles. Meanwhile, there will be a device applied over the muscles to record their contraction level.

The second part is to measure the muscle response timing. You will sit in front of a computer which will display some visual or audio signals. You will need to press a thumb switch and kick with the leg upon hearing or seeing a certain signals. A device will be attached to the knee cap to detect the leg movement and some skin electrodes will be attached to the thumb and thigh to record the muscle activities.

The third part is to measure your reflex action. You will stand on one leg with ear-shielded. The operator will suddenly perturb the back of your knee so as to elicit a stretch reflex in your knee muscles. A device will be attached to your knee cap to register the instant of perturbation and skin electrodes will be attached to the thigh to record the muscle activities.

This study will take place at a laboratory in PolyU. The above procedures do not have any known risk. Other than normal tingling sensation during electrical stimulation, you shall not have any pain or discomfort sensation.

Your involvement will not be of direct benefit to you. However, findings of this study will be useful in the design of training and assessment protocols for the athletes so that their levels of skill can be further enhanced and the rate of injury be reduced.

Consent:

I, ______________________, have been explained the details of this study. I voluntarily consent to participate in this study. I understand that I can withdraw from this study at any time without giving reasons, and my withdrawal will not lead to any punishment or prejudice against me. I am aware of any potential risk in joining this study. I also understand that my personal information will not be disclosed to people who are not related to this study and my name or photograph will not appear on any publications resulted from this study.

I can contact the investigator, Prof. Gabriel Ng, at telephone 2766-6721 for any questions about this study. If I have complaints related to the investigator(s), I can contact Mrs. Michelle Leung, secretary of Departmental Research Committee, at 2766-5397. I know I will be given a signed copy of this consent form.

Signature (subject): Date:

Signature (witness): Date:

Informed written consent form sample in Chapter 3 (Chinese version)

香港理工大學康復治療科學系科研同意書

科研題目: 跆拳道訓練對提高神經肌肉反應的機制的影響

監督人: 吳賢發教授 (香港理工大學康治療科學系副主任)

研究人員: 鍾綺雯 (香港理工大學康復治療科學系碩士研究生)

<u>科研簡介</u>

此科研計劃旨在測試高水平跆拳道運動員的肌肉興奮性、反射時間和平衡力，並與沒有接受此運動訓練的人比較。

肌肉興奮性是以電刺激於慣用手和腳上測試。研究人員會利用電極肌肉的最佳刺激位置；然後以不同程度的電流引發肌肉收縮。同時，會把記錄肌肉收縮程度的儀器貼於該肌肉上。

研究的第二部份是要測試肌肉反應時間。你需坐於電腦前，於電腦瑩幕出現指定聲音或視覺訊號時，盡快按動手中按鈕及踢腿。一個感應下肢活動的儀器會貼於膝蓋上；以及量度肌肉活動的表面電極會貼於姆指及大腿。

研究的第三部份是反射動作測試。你需單腳站立亦帶上耳罩。研究員會從後擾動你的膝部以引發膝關節的擴張神經反射。一個記錄膝部擾動時間的儀器會貼於膝蓋上；以及量度肌肉活動的表面電極會貼於大腿。

這研究會於香港理工大學的實驗室進行。本研究並無任何已知的潛在損害或危險性；除電刺激時感到的針刺感覺，研究過程中不會引致疼痛或不適感覺。

透過參與本研究對參加者未有直接得益，但研究所得的數據有助於爲運動員設計訓練和評估方案，藉此提高運動員的技術和降低受傷比率。

<u>同意書</u>

本人______________________________已瞭解此次研究的具體情況。本人願意參加此次研究，本人有權在任何時候、無任何原因放棄參與此次研究，而此舉不會導致我受到任何懲罰或不公平對待。本人明白參加此研究課題的潛在危險性以及本人的資料將不會洩露給與此研究無關的人員，我的名字或相片不會出現在任何出版物上。

若本人對此研究有何疑問，可致電研究人員鍾綺雯 (電話: 27665541)查詢。若本人對此研究人員有任何投訴，可以聯繫梁女士（部門科研委員會秘書），電話：2766 5397。本人亦明白，參與此研究課題需要本人簽署一份同意書。

參予者簽名: 日期:

見證人簽名: 日期:

Appendix VI

Raw Data of study in Chapter 3

Premotor reaction time

Group	Subject No.	Flexor pollicis brevis			Rectus femoris		
		Audio	Simple visual	Sport-specific visual	Audio	Simple visual	Sport-specific visual
Controls	1	200.33	193.00	245.00	149.00	213.00	260.67
	2	162.00	124.50	241.67	171.00	192.33	308.67
	3	112.00	142.00	228.00	103.33	148.00	304.00
	4	82.67	115.00	296.00	209.50	155.00	261.67
	5	156.00	199.33	288.67	173.67	195.50	253.33
	6	132.67	159.33	207.00	124.00	146.67	207.00
	7	183.67	201.67	303.33	177.67	248.00	393.00
	8	234.33	154.00	202.00	157.00	197.00	247.33
	9	163.33	186.33	228.33	155.33	161.67	182.00
	10	148.00	147.67	238.33	156.00	220.67	241.33
	11	136.33	174.00	311.33	174.00	189.33	327.00
	12	117.67	152.00	269.00	147.67	162.33	306.00
	13	146.67	114.67	214.33	147.33	145.00	210.00
	14	139.67	147.33	329.67	141.33	201.00	233.33
	15	119.00	164.33	339.00	136.67	149.33	256.33
	16	143.33	163.67	312.00	174.33	175.00	357.33
	17	130.33	142.67	247.67	150.00	140.33	235.00
	18	169.00	173.00	334.67	158.00	220.67	266.33
	19	155.00	152.67	238.67	169.33	205.33	248.67
	20	161.00	173.67	231.33	123.67	159.33	256.33
Amateur TKD practitioners	21	182.00	187.00	258.67	147.67	156.33	254.00
	22	136.00	179.67	259.67	143.67	157.67	263.00
	23	134.50	194.33	354.50	161.00	154.00	188.67
	24	166.50	173.33	175.33	124.50	192.67	212.33
	25	134.00	164.50	343.67	170.33	188.33	337.67
	26	121.33	152.00	261.67	154.00	164.00	263.00
	27	147.00	171.00	231.33	114.67	162.00	227.00
	28	134.33	148.00	221.67	166.33	168.00	250.33
	29	118.00	145.00	190.33	136.00	179.33	197.67
	30	88.00	113.00	138.33	124.67	158.00	188.00
	31	112.33	212.33	321.00	155.67	192.67	240.00
	32	143.00	150.00	214.00	152.67	165.33	246.00
	33	136.33	143.00	222.33	142.33	160.33	250.33
	34	96.67	128.00	265.00	169.00	153.67	311.33
	35	139.00	163.33	263.33	115.00	151.33	304.00
	36	151.00	149.33	200.33	152.33	139.33	235.67
	37	154.33	180.00	248.67	195.67	154.00	332.67
	38	112.67	148.33	169.00	150.00	188.33	305.67
	39	98.67	137.33	252.67	100.33	134.67	234.33
	40	112.67	134.00	265.00	125.67	150.00	259.33

Professional TKD practitioners	41	198.00	176.33	189.67	180.33	173.67	246.67
	42	205.33	151.67	223.00	251.33	193.33	237.33
	43	211.33	155.67	310.33	204.33	166.67	333.33
	44	215.00	145.00	231.33	252.67	190.00	288.33
	45	197.33	189.33	219.00	201.00	184.67	228.00
	46	221.67	171.00	327.00	249.67	177.00	283.33
	47	219.00	228.00	334.00	244.67	191.67	254.67
	48	181.00	188.33	188.67	200.33	181.67	176.00
	49	191.67	203.00	208.33	208.67	197.00	235.00
	50	205.33	198.67	218.33	250.00	236.67	301.00
	51	174.33	157.33	249.00	201.67	187.67	251.33
	52	221.67	218.00	226.00	234.00	242.00	271.00
	53	208.00	197.00	193.67	210.00	196.33	197.33
	54	213.67	157.67	229.00	244.67	209.67	337.33
	55	190.33	184.67	259.00	195.67	170.00	219.67
	56	151.67	152.33	163.00	173.00	194.67	263.33
	57	175.33	143.00	178.67	224.00	155.00	231.33
	58	180.00	228.67	204.00	201.33	186.67	198.00
	59	181.67	190.33	200.00	198.00	208.33	225.33
	60	202.33	174.00	207.67	214.00	208.67	223.00

Electromechanical Delay

Group	Subject No.	Flexor pollicis brevis			Rectus femoris		
		Audio	Simple visual	Sport-specific visual	Audio	Simple visual	Sport-specific visual
Controls	1	63.00	77.33	48.67	81.50	87.67	106.67
	2	65.33	57.00	68.67	78.00	77.33	72.33
	3	55.00	56.00	58.33	42.33	32.50	45.33
	4	103.00	72.33	53.33	75.50	79.33	46.67
	5	48.67	51.00	39.33	93.67	70.00	75.33
	6	56.33	46.00	96.00	76.50	128.33	96.00
	7	67.67	57.33	54.67	65.00	48.67	56.33
	8	78.67	80.67	76.33	49.33	51.00	55.33
	9	32.33	55.33	39.33	91.33	90.00	128.00
	10	47.67	44.00	38.33	61.67	47.33	56.00
	11	40.00	37.33	51.33	54.00	63.00	67.00
	12	59.67	58.00	51.67	21.33	22.33	18.33
	13	96.00	91.00	61.33	60.33	80.00	90.00
	14	58.00	65.00	63.33	53.00	57.33	60.67
	15	68.33	48.67	65.33	40.33	48.00	45.33
	16	71.67	77.67	78.33	12.67	18.33	15.67
	17	47.00	94.00	55.00	24.00	23.67	44.67
	18	52.33	57.33	58.33	34.33	42.33	70.67
	19	42.67	51.00	49.33	47.33	48.00	117.00
	20	47.00	46.33	66.00	13.67	10.00	21.67
Amateur TKD practitioners	21	49.00	39.67	51.00	72.00	69.67	79.33
	22	53.33	52.67	39.33	70.33	52.00	62.50
	23	40.00	44.00	45.50	39.33	47.00	40.33
	24	45.50	66.67	65.67	54.50	61.00	54.33
	25	74.00	67.50	37.67	78.67	50.33	47.67
	26	18.00	31.33	34.67	29.33	33.67	50.00
	27	42.33	43.33	41.67	66.33	63.67	64.00
	28	65.00	76.00	54.33	75.67	82.33	85.00
	29	61.33	44.67	46.33	67.00	60.00	91.00
	30	66.33	52.33	62.33	50.67	51.67	80.00
	31	60.00	44.67	35.00	54.33	79.67	100.00
	32	36.33	40.67	44.67	24.67	20.33	54.67
	33	41.33	44.67	37.67	38.67	16.00	21.00
	34	88.33	83.33	82.00	32.67	24.33	36.00
	35	47.33	49.67	35.00	58.67	55.33	58.33
	36	51.00	60.00	94.00	34.33	35.33	45.33
	37	39.33	53.33	55.00	20.67	12.33	35.67
	38	55.67	71.00	57.00	52.00	57.33	48.00
	39	54.67	65.00	64.67	26.67	39.33	38.67
	40	63.00	77.33	48.67	81.50	87.67	106.67

Professional TKD practitioners	41	79.00	66.67	95.33	116.00	103.67	97.67
	42	73.33	69.67	64.00	74.00	58.67	136.67
	43	56.67	59.67	50.00	36.00	40.00	43.00
	44	33.67	50.67	47.33	43.67	41.67	47.33
	45	55.33	66.67	55.00	46.00	47.33	44.33
	46	95.67	71.67	91.33	33.67	34.33	64.33
	47	54.00	53.00	55.67	39.67	48.67	85.67
	48	58.33	49.00	47.67	41.00	47.67	50.00
	49	45.67	44.67	44.33	12.00	23.67	14.67
	50	74.00	56.67	88.00	45.33	36.33	43.33
	51	71.00	72.00	89.67	26.67	50.00	62.00
	52	46.67	55.67	43.00	10.00	10.00	11.33
	53	71.33	55.33	106.00	55.33	54.00	28.00
	54	63.67	61.67	49.00	62.33	71.67	68.00
	55	49.67	56.00	65.00	31.67	28.00	54.67
	56	54.67	60.33	66.67	26.33	55.67	52.00
	57	73.33	68.67	90.67	7.67	18.00	15.33
	58	89.00	65.00	75.33	33.33	36.33	40.33
	59	84.00	61.67	45.00	130.33	114.67	115.67
	60	169.33	122.00	130.33	119.67	66.67	83.00

Total reaction time

Group	Subject No.	Flexor pollicis brevis			Rectus femoris		
		Audio	Simple visual	Sport-specific visual	Audio	Simple visual	Sport-specific visual
Controls	1	263.33	270.33	293.67	230.50	300.67	367.33
	2	227.33	210.00	310.33	249.00	269.67	381.00
	3	167.00	198.00	286.33	145.67	182.33	349.33
	4	185.67	187.33	349.33	285.00	234.33	308.33
	5	204.67	250.33	328.00	267.33	267.67	328.67
	6	189.00	205.33	303.00	200.50	275.00	303.00
	7	251.33	259.00	358.00	242.67	296.67	449.33
	8	313.00	234.67	278.33	206.33	248.00	302.67
	9	195.67	241.67	267.67	246.67	251.67	310.00
	10	195.67	191.67	276.67	217.67	268.00	297.33
	11	176.33	211.33	362.67	228.00	252.33	394.00
	12	177.33	210.00	320.67	169.00	184.67	324.33
	13	242.67	205.67	275.67	207.67	225.00	300.00
	14	197.67	212.33	393.00	194.33	258.33	294.00
	15	187.33	213.00	404.33	177.00	197.33	301.67
	16	215.00	241.33	390.33	187.00	193.33	373.00
	17	177.33	236.67	302.67	174.00	164.00	279.67
	18	221.33	230.33	393.00	192.33	263.00	337.00
	19	197.67	203.67	288.00	216.67	253.33	365.67
	20	208.00	220.00	297.33	137.33	169.33	278.00
Amateur TKD practitioners	21	231.00	226.67	309.67	219.67	226.00	333.33
	22	189.33	232.33	299.00	214.00	204.50	325.50
	23	176.00	238.33	400.00	200.33	201.00	229.00
	24	212.00	240.00	241.00	179.00	253.67	266.67
	25	208.00	232.00	381.33	249.00	238.67	385.33
	26	139.33	183.33	296.33	183.33	197.67	313.00
	27	189.33	214.33	273.00	181.00	225.67	291.00
	28	199.33	224.00	276.00	242.00	250.33	335.33
	29	179.33	189.67	236.67	203.00	239.33	302.00
	30	154.33	165.33	200.67	175.33	209.67	268.00
	31	172.33	257.00	356.00	210.00	272.33	340.00
	32	179.33	190.67	258.67	177.33	185.67	300.67
	33	177.67	187.67	260.00	181.00	176.33	271.33
	34	185.00	211.33	347.00	201.67	178.00	347.33
	35	186.33	213.00	298.33	173.67	206.67	362.33
	36	202.00	209.33	294.33	186.67	174.67	281.00
	37	193.67	233.33	303.67	216.33	166.33	368.33
	38	168.33	219.33	226.00	202.00	245.67	353.67
	39	153.33	202.33	317.33	127.00	174.00	273.00
	40	191.67	200.67	360.33	236.67	253.67	357.00

Professional TKD practitioners	41	271.33	246.00	253.67	254.33	232.33	383.33
	42	262.00	211.33	273.00	287.33	233.33	280.33
	43	245.00	206.33	357.67	248.00	208.33	380.67
	44	270.33	211.67	286.33	298.67	237.33	332.67
	45	293.00	261.00	310.33	234.67	219.00	292.33
	46	275.67	224.00	382.67	289.33	225.67	369.00
	47	277.33	277.00	381.67	285.67	239.33	304.67
	48	226.67	233.00	233.00	212.33	205.33	190.67
	49	265.67	259.67	296.33	254.00	233.33	278.33
	50	276.33	270.67	308.00	276.67	290.00	367.00
	51	221.00	213.00	292.00	208.67	197.67	262.67
	52	293.00	273.33	332.00	289.33	252.67	299.00
	53	271.67	258.67	242.67	272.33	268.00	265.33
	54	263.33	213.67	294.00	276.33	237.67	392.00
	55	245.00	245.00	325.67	222.00	225.67	271.67
	56	225.00	221.00	253.67	175.33	207.00	278.67
	57	264.33	208.00	254.00	257.33	191.33	271.67
	58	264.00	290.33	249.00	331.67	301.33	313.67
	59	351.00	312.33	330.33	317.67	275.00	308.33
	60	345.67	276.33	269.00	260.67	276.67	277.67

Rheobase

Group	Subject No.	Flexor pollicis brevis	Rectus femoris
Controls	1	0.9	7.2
	2	1.2	4
	3	0.9	3.3
	4	1.4	7.6
	5	1.4	4.8
	6	0.8	6.4
	7	0.9	9.7
	8	0.8	6
	9	0.7	7
	10	0.9	7.7
	11	0.7	5.2
	12	0.7	6.4
	13	1.1	4.8
	14	0.4	5.3
	15	1.1	4.8
	16	0.8	4.5
	17	1	5.4
	18	1	5.5
	19	0.7	3.2
	20	0.6	5.5
Amateur TKD practitioners	21	1.2	3.8
	22	0.9	5.2
	23	1.7	5.6
	24	0.9	5.4
	25	1.3	3.9
	26	0.7	7.3
	27	0.9	5.3
	28	0.7	
	29	1	8.5
	30	0.7	4.7
	31	1.2	5
	32	0.7	4.9
	33	1.3	4.7
	34	0.6	4.6
	35	0.8	5.8
	36	1.1	2.7
	37	0.9	7.5
	38	1	5.4
	39	1.1	5.8
	40	0.8	2.7

Professional TKD practitioners	41	2.6	3.7
	42	1.5	3
	43	1.9	3
	44	1.1	2
	45	1.7	3.3
	46	1.8	3
	47	1.8	2.9
	48	2.2	3.2
	49	1.8	3.1
	50	1.6	2.9
	51	1.3	2.6
	52	1.7	3.8
	53	1.6	2.8
	54	1.7	4.4
	55	1.9	5
	56	1.4	3.2
	57	1.7	3.4
	58	1.5	3.8
	59	1.4	3.1
	60	1.6	2.3

Appendix VII

Conference abstract for the 2010 Asics Conference of Science and Medicine in Sport

practices. Strategies including shade to reduce radiant heat, adequate ice cooling and insulated drink holders for beverages help to reduce the rise in beverage temperature to unpalatable ranges.

doi:10.1016/j.jsams.2010.10.634

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Upper limb strength of Malaysian tenpin bowlers: Relationship with bowling average and ball release velocity

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Introduction: Reasonable muscle strength is required to maintain full control of the heavy bowling ball and stay consistent throughout a tenpin bowling tournament. The aim of this study was to compare selected upper limb strength variables in bowlers with the normal population. In addition, the study examined how these strength variables relate to bowling scores and ball release velocity. *Methods*: 17 male (age 22.4 ± 3.6 years) and 13 female (age 21.7 ± 4.8 years) national bowlers were measured, while 14 male (age 22.0 ± 1.6 years) and 19 female (age 22.6 ± 1.4 years) sedentary university students were assigned to the normal population group. Isometric strength tests were taken on the dominant side and scores were normalized to body mass. The measurements were finger pinch force between the index to thumb, middle finger to thumb, third finger to thumb, arm flexion, wrist flexion, internal rotation and external rotation. The bowlers also had their bowling scores averaged over three tournaments and ball release velocity recorded. Significance level was set at $p < 0.05$. *Results and discussion*: The male bowlers significantly differed from the normal population in arm flexion ($t29 = 3.48$), wrist flexion ($t29 = 2.75$) and internal rotation ($t29 = 2.71$), while the females differed only in internal rotation ($t30 = 2.01$). It is unclear whether these differences were a result of the bowlers having more strength to begin with or gained strength through bowling participation. In addition, results indicate that arm flexion ($r = 0.55$), wrist flexion ($r = 0.45$), internal ($r = 0.51$) and external rotation ($r = 0.62$) were all significantly correlated with ball release velocity, but more importantly was that none of the strength variables were related to the average bowling score. Furthermore, no significant relationship existed between ball release velocity and average bowling performance. Therefore, even though upper limb strength seems essential to ball release velocity, the impact it has on a bowler's average seem insignificant. In conclusion, there is a difference in upper limb strength between bowlers and the normal population, but further research is necessary to find cause and effects relationship of bowling participation. The results also suggest that some form of upper limb strength is required in delivering the ball at high velocities but its relationship to the overall bowling score is negligible. Finally, as it was observed that internal rotation was present in all significant comparisons and correlations, it appears to be a key strength element in bowling and thus warrants further investigation.

doi:10.1016/j.jsams.2010.10.635

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Effects of Taekwondo training on neuromotor control of large and small muscles

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Introduction: Fast reactions are important for good competitive performance in combat sports such as Taekwondo (TKD). Hitherto, no study has investigated the effect of TKD training on the neuromotor control mechanism thus this study aimed to examine the difference in pre-motor time, movement onset timing and electromechanical delay (EMD) between skilled TKD practitioners and non-athletes. *Methodology*: 20 professional TKD athletes, 20 amateur TKD practitioners and 20 non-athletes aged 18–29 years participated. Reaction timing of flexors pollicis brevis (FPB) and rectus femoris (RF) to audio stimulus, non-sport specific and sport specific visual stimuli was tested. The audio stimulus was a "beep" sound, the non-sport specific visual stimulus was a green light appearing randomly on a computer screen whereas the sport specific stimulus was an attack motion image popped up on the computer screen. Subjects responded to the stimuli by pressing a switch with their dominant thumb or kicking with their dominant leg, on which an accelerometer was attached to the tibial tuberosity. Surface electromyography (EMG) of FPB and RF was recorded and the time lag between the stimuli and EMG onset was determined as the pre-motor time. Movement onset of the thumb and leg was indicated by triggering of the thumb switch and the accelerometer signals respectively. EMD was measured by the time lapse between EMG onset and movement onset. *Results*: Professional TKD practitioners showed significantly longer pre-motor time and movement onset of FPB ($p < 0.01$) and RF ($p < 0.01$) to audio stimulus comparing to other two groups. Slower movement onset of FPB ($p = 0.022$) and RF ($p = 0.001$) to the non-sport specific visual stimulus was also found in professional TKD practitioners. However, professional TKD athletes have shorter pre-motor time of FPB 228 ms ($p = 0.03$) and RF 250 ms ($p = 0.51$) to sport specific visual stimulus than non-athletes. No significant difference in EMD was found between three groups. *Discussion*: Professional TKD athletes were found to have slower reactions to simple audio and visual stimuli, but faster reactions to sports specific pictures comparing to amateur TKD players and controls. Slower reaction times to simple stimulus may indicate that intensive TKD training inhibits the athletes' sensitiv-

Appendix VIII

Conference abstract for the 7th Pan-Pacific Conference on Rehabilitation & 2010 Graduate Student Conference on Rehabilitation Sciences

EFFECTS OF TAEKWONDO TRAINING ON NEUROMOTOR EXCITABILITY AND REACTION OF LARGE AND SMALL MUSCLES.

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Background and Purpose:

Taekwondo (TKD) training involves frequent jumping and kicking, which requires skillful motor control, might improve reactions and neuromotor control of the body. This study measured the neuromotor performance in elite and amateur TKD practitioners and compared that with non-athletes.

Methods:

20 elite, 20 amateur TKD practitioners and 20 non-athletes were studied. Neuromotor excitability (rheobase), premotor reaction time (PRT), total reaction time (TRT) and electromechanical delay of flexor pollicis brevis (FPB) and rectus femoris (RF) in response to audio and visual stimuli were measured. Data were analyzed by ANCOVA with height as the covariate.

Results:

Elite TKD practitioners have longer PRT and TRT in response to audio stimuli than the other two groups in both FPB (PRT: $p<0.001$; TRT: $p<0.001$) and RF (PRT: $p<0.001$; TRT: $P<0.001$). The TRT of elite TKD practitioners was shorter than non athletes to sport-specific visual stimuli in FPB ($p=0.026$) and RF ($p=0.038$). The elite TKD practitioners had significantly longer EMD than the amateur practitioners to audio ($p=0.032$) and sports-specific visual stimuli ($p=0.03$) in FPB. Elite TKD practitioners had higher excitability in RF ($p<0.001$) comparing to amateur practitioners and non athletes.

Conclusion:

Elite TKD practitioners have better neuromotor ability with faster reactions to sport-specific visual stimuli in both large and small muscles and higher neuromotor excitability in the large muscle. Elite TKD practitioners were found to react slower to non-sport specific stimuli.

EFFICACY OF ANTI-PRONATION DEVICES: A META-ANALYSIS.

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Background and Purpose:

Orthosis, motion control shoe and taping are 3 common anti-pronation devices, but their efficacy remains equivocal. The purpose of this study was to review all published data fulfilling specified inclusion criteria, and to compare the efficacy of anti-pronation devices in reducing foot pronation.

Methods:

Thirty two were found from the MEDLINE, EMBASE, CINAHL and AMED databases that fulfilled the inclusion criteria of being English articles with relevant outcome measures. The pooled effect sizes and relative strength of effects were calculated for each device by forest plots with Review Manager version 5.0.

Results:

All three anti-pronation devices were effective in foot movement control ($p<0.001$). In reducing foot pronation, taping was more effective (mean difference=2.64° [1.39, 3.90], $Z=4.13$) than orthosis (mean difference=2.24° [1.41, 3.07], $Z=5.29$) and motion control shoe (mean difference=2.52° [1.71, 3.33], $Z=6.10$). Low-dye taping was not better than other taping techniques (mean difference=2.10° versus 4.48°). Custom made orthosis was superior to non custom made orthosis (mean difference=2.43° versus 1.77°) and motion control shoe with duo material in the midsole was better than footwear with heel flare or wedge design (mean difference=3.46° versus 1.85°).

Conclusion:

Orthosis, motion control shoe and taping are effective in controlling excessive foot pronation. The results suggested that taping may be more effective for checking foot pronation than the other two devices. However, difference in efficacy between different approaches or application methods exists and intervention selection should be cautioned.

Appendix IX

Physical Therapy in Sport 13 (2012) 163–169

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original research

Taekwondo training improves the neuromotor excitability and reaction of large and small muscles

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ARTICLE INFO

Article history:
Received 28 March 2011
Received in revised form
4 July 2011
Accepted 11 July 2011

Keywords:
Taekwondo
Reaction
Neuromotor excitability
Muscles
Motor control

ABSTRACT

Objectives: This study measured the neuromotor excitability and reaction time in professional and amateur Taekwondo (TKD) practitioners and compared them with non-athletes.
Design: A cross-sectional cohort study design.
Setting: Exercise laboratory setting.
Participants: 40 TKD practitioners (20 professionals, 20 amateurs) and 20 non-athletes.
Main outcome measures: Neuromotor excitability (rheobase), premotor reaction time (PRT), total reaction time (TRT) and electromechanical delay (EMD) of rectus femoris (RF) and flexor pollicis brevis (FPB) in response to audio and visual stimuli were measured. The professional TKD practitioners have shorter TRT than non-athletes with sport-specific visual stimuli but they have longer PRT and TRT in response to audio stimuli than the amateur practitioners and non-athletes.
Results: The professional practitioners have longer EMD than the amateurs in responding to audio ($p = 0.032$) and sports-specific visual stimuli ($p = 0.03$) in FPB. Professional practitioners have higher excitability in RF ($p < 0.001$) than the amateurs and non-athletes.
Conclusion: We conclude that professional TKD practitioners have better neuromotor ability in both large and small muscles with faster reactions to sport-specific stimuli, suggesting a generalized training effect across muscles. They react slower to non-sport specific stimuli, which suggested a decreased sensitivity to irrelevant sensory inputs after intensive TKD training.

1. Introduction

Reaction time is an index of sensori-motor performance in sports and is important in predicting the risk of sports injury (Nakamoto & Mori, 2008). The total reaction time (TRT) is the period between the appearance of a stimulus to the onset of force production by the responding muscles and it can be divided into premotor reaction time (PRT) and electromechanical delay (EMD). PRT is the latency between the appearance of a stimulus and onset of EMG activities (Schmidt & Lee, 1999), which denotes the speed of neural transmission and information processing. Whereas, EMD is the interval between onset of EMG signal and force production (Cavanagh & Komi, 1979), which reflects the neuro-mechanical properties of the muscles. Identification of the difference in each component of TRT will enable the understanding of the effects of sports training on the neural transmission and excitation-contraction coupling in motor control.

There is an increasing popularity in combat fighting sports and among them, Taekwondo (TKD) is a very popular sport practiced by some 80 million people in over 180 countries (WTF 2009). Faster reaction time was found in TKD experts compared to novices as in many other sports (Kida, Oda, & Matsumura, 2005; Kioumourtzoglou, Kourtessis, Michalopoulou, & Derri, 1998; Lee, Kin, & Song, 2010; Mero, Jaakkola, & Komi, 1989; Nakamoto & Mori, 2008). A number of researchers have attributed the faster reaction times in athletes as due to their better perceptual and cognitive abilities in their sports (Helsen & Starks, 1999; Kioumourtzoglou et al., 1998; Mori, Ohtani, & Imanaka, 2002).

According to the literature, the effect of sports expertise on reaction time is domain specific. Helsen and Starks (1999) reported that elite soccer players had significantly faster reaction times to sports-specific visual stimulation than the amateurs whereas no difference was found between the two groups with non-sport specific visual stimuli. More recently, Borysiuk and Bailey (2007) found that fencers reacted fastest to tactile stimuli followed by acoustic and visual stimuli. The authors suggested that the use of fencing gears enhanced the reactions to tactile stimulation in fencers. Despite the combating nature in TKD, the athletes receive

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1466-853X/$ – see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.ptsp.2011.07.003

no tactile stimulation from the opponents before they are attacked, therefore visual and audio signals become essential in determining the opponents' actions.

Hitherto, there has only been one study (Song & An, 2004) investigating the effect of TKD training on reaction time and it was done on people with learning difficulties. Results of that study showed that a 7-month TKD training had improved the EMD in the participants but no significant effect on PRT. However, since that study was done on people with learning difficulties, its finding may not be directly applicable to people with normal cognition. The present study therefore aimed at exploring the neuromotor effects of TKD training by examining the reaction time to different stimuli and muscle excitability in elite and amateur TKD athletes and comparing them with people not involved in this sport. Findings of this study will establish a scientific basis for optimizing training of TKD athletes and improving the attributes that are important to the performance in this sport.

2. Methodology

2.1. Participants

This study was done with a purposive sampling of 3 groups of participants. Group 1 comprised 20 professional TKD athletes (15 males) aged 18–23 years (Mean age 19 years) who have received 3–11 years of intensive TKD training in a provincial team. These participants received TKD training 6 h per day for 5–6 days per week. Group 2 comprised 20 amateur TKD practitioners (10 males) aged 19–24 years (Mean age 21 years) from the TKD clubs of local tertiary institutions. These participants have less than 3 years of TKD experience with 6–9 h of training per week. Group 3 comprised 20 healthy individuals (12 male) aged 19–29 years (Mean age 23 years) who were not involved in any regular sports training. Participants with a history of surgery or injury requiring medical attention in the previous six months were excluded. This study was approved by the administrating institution and all the participants gave their written informed consent prior to the tests.

2.2. Measurements

2.2.1. Reaction time and electromechanical delay

Reaction timing to audio stimulus, simple visual stimulus and sport-specific visual stimulus was tested. Subjects wore a pair of ear phones and sat at 1.5 m in front of a computer monitor with hips and knees flexed at 90°. The subject held a thumb switch on the dominant hand and a uniaxial accelerometer (Model 8772A10, Kistler Instrument Corp, Amherst, NY, USA) was attached to the tibial tuberosity of the dominant leg to register the movement of the thumb and leg, respectively.

Double-differential surface EMG electrodes with inter-electrode distance of 3.5 cm (BL-AE-WG, B&L Engineering, Santa Ana, CA, USA) were applied over the muscle bulk of flexor pollicis brevis (FPB) and rectus femoris (RF) (Freriks, Hermens, Disselhorst-Klug, & Rau, 1999). The common mode rejection ratio of the electrodes was 95 dB and input impedance was 100MΩ. The EMG signals were pre-amplified by 330 times and band-pass filtered between 10 Hz and 312 Hz. Standard skin preparation procedures were performed to reduce skin impedance.

The audio stimulus was a single beep sound on a quiet background from the ear phones. The simple visual stimulus was a green circle appearing spontaneously on a gray background of the computer monitor, whereas the sport-specific visual stimulus was a photograph of a TKD athlete performing a side kick attack motion preceded by a series of photographs of the athlete in guarding form. The test was repeated 4 times for each stimulus.

Upon the onset of each stimulus, subjects responded by pressing the thumb switch and kicking with the dominant leg as fast as possible. Amplified EMG signals together with signals from the thumb switch and accelerometer were sent to an analog-digital converter with a sampling rate of 1000 Hz (DAQPad-6020E, National Instrument, TX, USA) and recorded by LabVIEW software (National Instruments, TX, USA) for off-line analysis. The EMG data were full-wave rectified and onset of muscle contraction was defined as a signal with at least 2 standard deviations higher than the mean resting EMG signal and lasting for more than 10 ms (McKinley & Pedotti, 1992). PRT is the time lapse between the appearance of stimulus and onset of EMG activities, while EMD is the time lapse between onset of EMG activities and force registration by the thumb switch or accelerometer.

2.2.2. Neuromuscular excitability

The neuromuscular excitability of FPB and RF muscles was assessed by electrical stimulation method according to Robertson, Ward, Low, and Reed (2006). The FPB and RF were tested with a constant current stimulator (Endomed 581, Enraf-Nonius, Rotterdam, Netherlands). An active pointer electrode was applied on the motor points of the muscles being tested and a pad dispersive electrode was placed at 4 cm proximal to the active electrode. The active electrode was held with a stand which could maintain the position and pressure during the testing procedure (Fig. 1).

In order to quantify the level of muscle contraction, an air-coupled pulse transducer head (Pulse Transducer Head 03040000, Cambridge Instrument Company Inc., Ossining, NY, USA) was applied over the muscles to measure the mechanomyographic (MMG) signals (Wong, Chan, Tang, & Ng, 2009) (Fig. 1). Before the test, 200 ms of resting MMG signals were captured to establish the resting muscle activity level. Any signal with more than 2 standard deviations (SD) higher than the mean resting MMG signal would be defined as the minimal detectable muscle contraction. The transducer was connected to an analog-digital converter with a sampling rate of 1000 Hz (DAQPad-6020E, National Instrument, TX, USA). Two reference lines indicating the threshold values and real-time MMG signals were displayed on the computer monitor.

To determine the threshold current, the amperage was slowly increased until the MMG signals exceeded the threshold values for 10 pulses in succession. The threshold current intensity at pulse durations of 200, 100, 50, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1 and 0.05 ms were recorded and the current required to elicit a muscle contraction with 200 ms of pulse duration was defined as the rheobase. Although only the threshold current at the longest pulse duration was used for analysis, the standard practice of testing 10-15 different pulse durations from 200 ms to 0.05 ms for determining rheobase was followed (Alexander, 1974; Nelson & Hunt, 1981; Robertson et al., 2006). The reason for applying multiple pulse durations was to construct a complete strength duration curve and the shape of the curve would be studied for any abnormality of the muscle electrical response.

2.3. Data analysis

The age, weight, height and body mass index (BMI) between groups were compared with one-way analysis of variance (ANOVA). The mean values of PRT, TRT and EMD to the three stimuli between groups were analyzed by two-way analysis of covariance (ANCOVA) (3 groups × 3 stimuli) with height as the covariate. When significant main effects were found, one-way ANCOVA with Bonferroni adjusted post-hoc pair-wise comparison were performed to identify specific difference between groups. Differences in rheobase between groups for the two muscles were analyzed with one-way

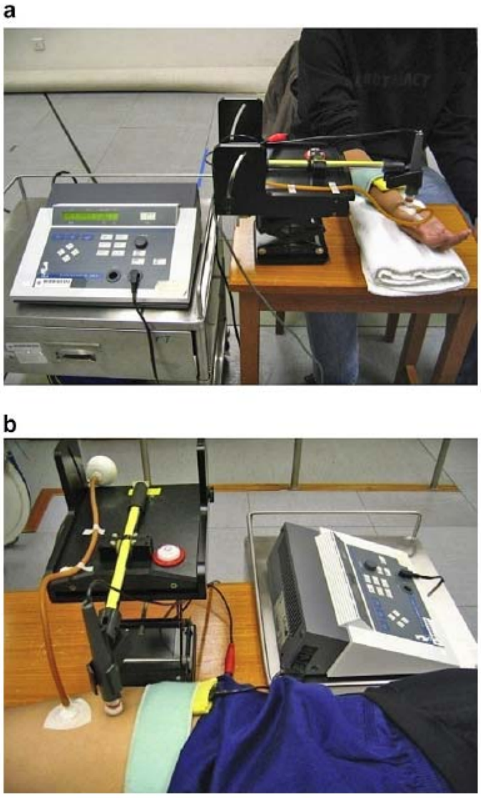


Fig. 1. The setup of strength duration testing for flexor pollicis brevis (a) and rectus femoris (b). The active electrode is stabilized by a clamp and applied on the muscle bulk. And air-coupled transducer head is applied on the muscle to record the mechanomyographic signals.

ANCOVA with height as the covariate. Significance level was set as 0.05 for all the tests.

3. Results

Demographic data for the participants are shown in Table 1. A significant difference was found in age ($p < 0.001$), height ($p < 0.001$) and weight ($p = 0.001$) among the three groups. In view that height has a strong correlation with nerve conduction velocity (Rivner, Swift, & Malik, 2001) which may affect reaction time, this parameter was therefore included as a covariate term in the statistical model. Results of TRT, PRT, EMD and rheobase are shown in Tables 2 and 3. Significant group effects were found in EMD for FPB ($p = 0.014$) and PRT for RF ($p = 0.024$).

Table 1
Demographic data for three groups of participants (Mean ± SD).

	Professional	Amateur	Non-athletes
Age (years)	19 ± 1.9	21 ± 1.3	23 ± 3.5
Gender (n)			
Male	15	10	12
Female	5	10	8
Height (cm)	181.0 ± 7.23	164.3 ± 10.09	169.2 ± 9.59
Weight (kg)	67.1 ± 8.74	56.3 ± 8.52	60.2 ± 9.50
BMI (kg/m^2)	20.4	20.8	20.9
TKD experience (years)	5.3 ± 1.98	1.9 ± 0.57	

Table 2
Mean (SD) of total reaction time, premotor reaction time, electromechanical delay and rheobase of flexor pollicis brevis for different stimulus.

	Stimulus	Professional	Amateur	Non-athletes
Premotor reaction time (ms)	Audio	197 (18.8)	131 (23.7)[a]	150 (33.0)[a]
	Visual	181 (26.6)	159 (24.3)	159 (25.2)
	Sports-specific	228 (47.3)	243 (55.5)[b]	265 (44.9)[b]
Electromechanical delay (ms)	Audio	73 (32.4)	53 (16.3)[b]	60 (17.4)
	Visual	65 (18.1)	55 (13.9)	61 (15.9)
	Sports-specific	68 (24.0)	54 (18.7)[b]	59 (14.2)
Total reaction time (ms)	Audio	270 (33.4)	184 (21.4)[a]	210 (35.6)[a]
	Visual	246 (31.6)	214 (22.9)	222 (22.8)
	Sports-specific	296 (44.8)	297 (53.0)	324 (45.3)[b]
Rheobase (mA)		1.7 (0.32)	1.0 (0.27)[a]	0.9 (0.25)[a]

[a] Significantly different from professional TKD practitioners with $p < 0.01$.
[b] Significantly different from professional TKD practitioners with $p < 0.05$.

3.1. Premotor reaction time

One-way ANOVA with post-hoc pair-wise comparisons revealed that professional TKD practitioners have longer PRT to audio stimulus than the amateurs and non-athletes. The professional practitioners also have longer PRT to simple visual stimulus for RF than amateurs, but shorter PRT to sport-specific visual stimulus for FPB comparing to amateurs and non-athletes (Fig. 2).

3.2. Electromechanical delay

The post hoc test results revealed that the amateurs have shorter EMD in FPB than the professionals in response to audio and sport-specific visual stimuli (Fig. 3).

3.3. Total reaction time

Post-hoc pair-wise comparison showed that the professional TKD practitioners have longer TRT than the amateurs and non-athletes to audio stimulus, whereas both groups of TKD practitioners have shorter TRT than the non-athletes to sport-specific visual stimulus in RF and FPB (Fig. 4).

3.4. Rheobase

The rheobase was significantly higher for FPB, but lower for RF in the professional practitioners than the amateurs and non-athletes (Fig. 5).

Table 3
Mean (SD) of total reaction time, premotor reaction time, electromechanical delay and rheobase of rectus femoris for different stimulus.

	Stimulus	Professional	Amateur	Non-athletes
Premotor reaction time (ms)	Audio	217 (25.0)	145 (22.9)[a]	155 (23.3)[a]
	Visual	193 (21.4)	164 (16.8)[b]	181 (31.2)
	Sports-specific	250 (42.8)	255 (44.2)	268 (51.5)
Electromechanical delay (ms)	Audio	46 (31.7)	53 (23.5)	54 (24.7)
	Visual	48 (22.8)	51 (23.4)	56 (29.0)
	Sports-specific	56 (31.6)	60 (22.5)	65 (31.2)
Total reaction time (ms)	Audio	263 (38.4)	198 (28.4)[b]	208 (39.6)[b]
	Visual	238 (30.9)	214 (32.3)	237 (41.8)
	Sports-specific	306 (51.2)	315 (42.0)	332 (44.4)[b]
Rheobase (mA)		3.2 (0.68)	5.2 (1.47)[b]	5.7 (1.59)[a]

[a] Significantly different from professional TKD practitioners with $p < 0.01$.
[b] Significantly different from professional TKD practitioners with $p < 0.05$.

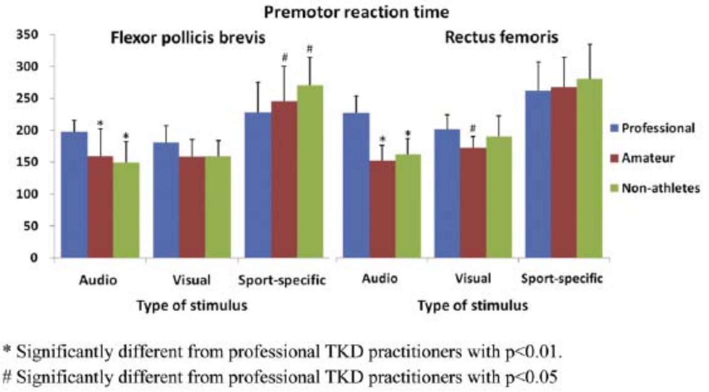


Fig. 2. Premotor reaction time of rectus femoris to three type of stimulus.

4. Discussion

According to Kazemi, Waalen, Morgan, and White (2006), kicks would account for over 90% of the techniques for scoring in TKD matches. Based on the reports that exercise training is muscle-specific (Ellenbecker & Roetert, 2003; Mausour, Maisetti, Cornu, & Portero, 2005), the neuromotor performance of large muscles of the lower limbs would be expected to improve after TKD training, but not the small hand muscles as they are not involved in the training. Therefore, a large muscle (RF) and a small muscle (FPB) were selected for comparison.

Our findings revealed that professional TKD athletes reacted faster to sport-specific visual stimulus but slower to plain audio stimulus than the amateurs and non-athletes. The faster PRT and TRT in elite athletes could be due to improvements in their sports specific cognition. Mori et al. (2002) found that karate athletes could predict the attack motions of their opponents earlier than novices when shown pictures of attack forms. They suggested that the faster reaction to a sport-specific stimulus was due to better anticipatory skills in trained athletes. Similarly, Helsen and Starks (1999) reported that elite soccer athletes responded faster to a test that simulated football match and attributed that to their superior information processing ability in the athletes in making a tactical decision with the ball as in a real game.

Although the sport-specific stimulus used in this study was a static display of TKD pictures which did not involve a decision making component, the shorter TRT and PRT in professional TKD practitioners would indicate that they have faster perceptual speed in discrimination of the sport-specific postures than the novice and non-athletes. Moreover, we found that shortened reaction time to sport-specific stimulus was not limited to the muscles trained in TKD, which means this central processing is common in both the trained and untrained muscles.

An interesting finding is that the professional practitioners had longer TRT and PRT in responding to audio and simple visual stimuli. This finding is original and has never been reported before. Previous researchers had either found no difference in simple reaction time between professionals and novices (Helsen & Starks, 1999; Kida et al., 2005; Ripoll, Kerlirzin, Stei, & Reine, 1995) or shorter reaction time in the professional practitioners (Mori et al., 2002) or non-athletes (Ando, Kida, & Oda et al., 2002; Kokubu, Ando, Kida, & Oda, 2006; Nakamoto & Mori, 2008). Herpin et al. (2010) studied the sensori-motor specificities in balance control of fencers and pistol shooters and found these athletes to have shifted their visual attention to the most relevant information. Besides, the authors also found that the athletes had utilized more of the vestibular and proprioceptive cues for balance control. Similarly, Paillard et al. (2006) found that with improved sports

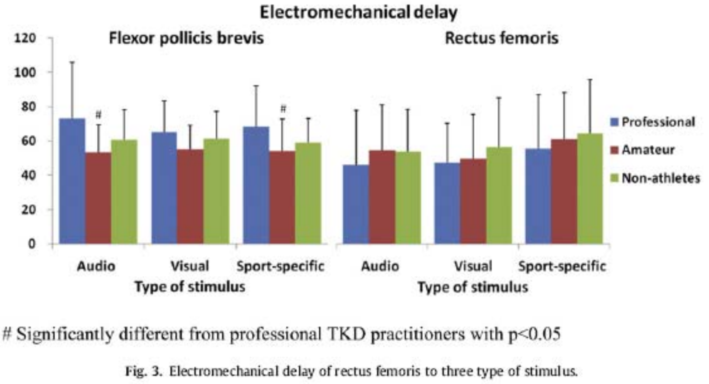
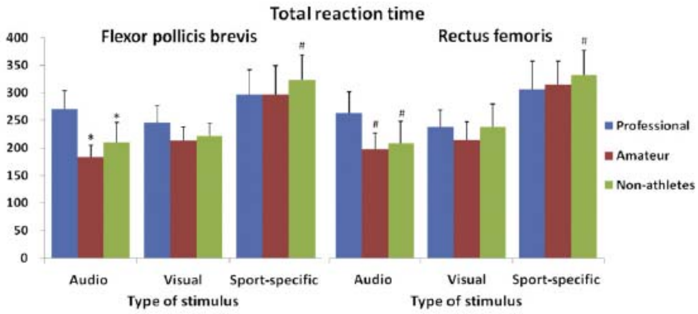


Fig. 3. Electromechanical delay of rectus femoris to three type of stimulus.



* Significantly different from professional TKD practitioners with p<0.01.
# Significantly different from professional TKD practitioners with p<0.05

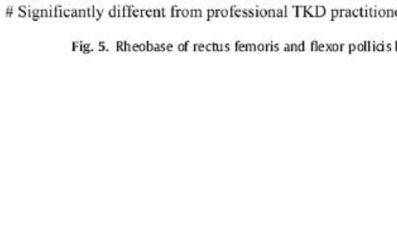
Fig. 4. Total reaction time of rectus femoris to three type of stimulus.

skills, there would be less dependence on visual cues for postural control.

Focusing on the opponent's movement is extremely important during TKD combat fighting as the athletes need to differentiate real offensive movements from feint and look for opportunities to attack. Therefore, the professionals may focus their visual or audio attention to the combat scene rather than those background audio–visual noises. It is possible that intensive TKD training would lead to shifting of attention to the most important information of the match and decrease the sensitivity towards irrelevant signals such as flash lights or chanting from spectators.

EMD is the time gap between onset of muscle activities and force production. However, very few studies have looked at the characteristics of EMD in professional athletes and none had compared the EMD of professionals with amateurs and non-athletes. Since EMD has been shown to be related to maximum voluntary contraction (MVC) (Zhou, 1995) and TKD training would lead to increase in lower limb muscle strength (Tsokovic, Blessing, & Williford, 2002), shorter EMD in professional practitioners would be expected. Although not significant, the professionals showed consistent trends of shorter EMD in RF to all stimuli.

The lack of standardized response movement could have contributed to the insignificant findings. During the reaction time test, subjects were asked to kick as fast as possible in response to the stimulus with a standardized starting position, but the speed and force of the kicking action were not controlled. As EMD is related to the rate of force development (Zhou, 1995) and percentage of MVC (Yavuz, Sendemir-Urkmez, & Turker, 2010), the variation in kicking speed and force among subjects might have caused the large variability in EMD and leading to insignificant findings.



* Significantly different from professional TKD practitioners with p<0.01.
# Significantly different from professional TKD practitioners with p<0.05

Fig. 5. Rheobase of rectus femoris and flexor pollicis brevis.

The EMD of RF found in this study is longer than those reported in other studies (Table 4). This could be due to differences in methodologies because EMD was measured during MVC in other studies while subjects in this study performed knee extension without loading. Since EMD is negatively correlated with contraction level (Yavuz et al., 2010), therefore the lower contraction level used in this study may have led to longer EMD.

There were no interaction effects found between stimulus and group in EMD which indicated that EMD was not affected by the type of stimulus. It signified that, unlike PRT, EMD did not involve a cognitive component and it only reflects the physiological properties of the muscles. Furthermore, the effects of TKD training on this physiological process were confined to the trained muscles as the trend of shorter EMD in the professional practitioner were found in RF only.

Neuromotor excitability is postulated to be related to the ionic gradient across the sarcolemma and T-tubular membranes (Yerdelen, Uysal, Koc, & Sarica, 2006) and is closely regulated by the sodium/potassium (Na^+/K^+) pumps capacity. Previous studies that examined muscle excitability by Na^+/K^+ pump concentration in muscle biopsies reported the increase in Na^+/K^+ pump concentration could be facilitated by various kinds of physical training, which would lead to increase in neuromotor excitability and better contractile performance (Clausen, 2003; Medbø, Jebens, Vikne, Refsnes, & Gramvik, 2001). Naturally, the neuromotor excitability of muscles would be expected to increase with sports training that require fast reaction.

The electrophysiological strength duration testing is a non-invasive method for determining the neuromuscular excitability (Irnich, 2010) and it has been used to investigate the pathophysiology of several diseases that are suspected to affect axonal excitability such as diabetes mellitus and renal failure (Yerdelen et al., 2006). Higher rheobase in vastus medialis muscle was found in children with lateral patellar stability, indicating lower muscle excitability in patients with neuromotor dysfunction (Kaczmarek, Wysokinska, & Zytkowski, 2008).

We found that the professionals have lower rheobase in their knee extensors thus higher excitability in these muscles. As a higher excitability is suggestive of better muscle contractility and fatigue resistance (Clausen, 2003), this could be an important factor for maintaining one's ability in performing powerful and effective kicks

Table 4
Review table of electromechanical delay.

Studies	Subjects	Testing methods	Electromechanical delay (ms)		
			Athletes	Novices	Non-athletes
Current study	Professional TKD practitioners: 19 years Amateur TKD practitioners: 21 years Non-athletes: 23 years	Knee extension in response to light stimulus	48	51	56
Kubo, Kanehisa, Ito, & Fukunaga, 2001	Non-athletes: 22.6years	Knee extension MVC performed as rapidly as possible			52.6
Zhou, 1995	Endurance athletes	Knee extension MVC in response to light signal	43		
Zhou, 1995	Weight lifters		34.9		38.1
Zhou, McKenna, Lawson, Morrison, & Fairweather, 1996	Non-athletes: 18.8years				38

during TKD competitions. Lower rheobase was found in the trained muscles only, which is in line with previous findings that training effect on neuromotor excitability is muscle-specific (Clausen, 2003).

The results revealed that PRT had occupied a large portion of the TRT, and this suggests that PRT is a more important determining factor of the neuromotor performance compared with EMD. This implied that involving a cognitive component in the TKD training program could be beneficial to the athletes' performance. The better performance by elite athletes in sport-specific tasks was thought to be related to the better knowledge of the game situation, such as more accurate interpretation of the opponent's movement and other environmental cues by the athletes (Abernethy & Zawi, 2007; Helsen & Starks, 1999; Müller, Abernethy, Eid, McBean, & Rose, 2010), therefore training the athletes' sport-specific cognitive components could be beneficial to their performance.

5. Conclusion

Professional TKD practitioners receiving long-term intensive training have better neuromotor performance than amateurs and non-athletes by demonstrating a faster reaction to sports-specific stimulus and better physiological performance in terms of higher excitability in the trained muscles. We also conclude that professional TKD practitioners react slower than amateurs and non-athletes to non-sports specific stimuli, which suggests a decrease in sensitivity to irrelevant sensory inputs after long-term intensive TKD training.

Conflict of interest

None declared.

Ethical approval

The authors declare that they have observed and adhered to the ethical principles normally practiced in the field of medical science in the acquisition, interpretation and condensation of the information for writing this paper.

Funding

None declared.

References

Abernethy, B., & Zawi, K. (2007). Pickup of essential kinematics underpins expert perception of movement patterns. *Journal of Motor Behaviour, 39*, 353–367.

Alexander, J. (1974). Reproducibility of strength-duration curves. *Archives of Physical Medicine, 55*, 56–60.

Ando, S., Kida, N., & Oda, S. (2002). Practice effects on reaction time for peripheral and central visual fields. *Perceptual Motor Skills, 95*, 747–751.

Borysiuk, Z., & Bailey, R. (2007). Influence of stimuli type on electromyography (EMG) signal, reaction and movement time in novice and advanced fencers. *Journal of Human Movement Studies, 52*, 65–79.

Cavanagh, P. R., & Komi, P. V. (1979). Electromechanical delay in human skeletal muscle under concentric and eccentric conditions. *European Journal of Applied Physiology, 42*, 159–163.

Clausen, T. (2003). Na^+-K^+ pump regulation and skeletal muscle contractility. *Physiological Review, 83*, 1269–1324.

Ellenbecker, T., & Roetert, E. P. (2003). Age specific isokinetic glenohumeral internal and external rotation strength in elite junior tennis players. *Journal of Science & Medicine in Sport, 7*, 62–70.

Freriks, B., Hermens, H., Disselhorst-Klug, C., & Rau, G. (1999). The recommendations for sensors and sensor placement procedures for surface electromyography. In H. J. Hermens, B. Freriks, R. Merletti, D. Stegeman, J. Bolk, G. Rau, C. Disselhorst-Klug, & G. Hagg (Eds.), *European recommendations for surface electromyography: results of the SENIAM project* (pp. 12–25). The Netherlands: Roessingh Research and Development.

Helsen, W. F., & Starks, J. L. (1999). A multidimensional approach to skilled perception and performance in sport. *Applied Cognitive Psychology, 13*, 1–27.

Herpin, G., Gauchard, G. C., Lion, A., Collet, P., Keller, D., & Perrin, P. P. (2010). Sensorimotor specificities in balance control of expert fencers and pistol shooters. *Journal Electromyography and Kinesiology, 20*, 162–169.

Irnich, W. (2010). The terms "chronaxie" and "rheobase" are 100 years old. *Pacing and Clinical Electrophysiology, 334*, 491–496.

Kaczmarek, K., Wysokinska, A., & Zytkowski, A. (2008). Evaluation of vastus medialis excitability in children with lateral patellar instability. *Ortopedia, Traumatologia, Rehabilitacja, 10*(6), 583–592.

Kazemi, M., Waalen, J., Morgan, C., & White, A. R. (2006). A profile of Olympic taekwondo competitors. *Journal of Sports Science and Medicine, 5*, 114–1121.

Kida, N., Oda, S., & Matsumura, M. (2005). Intensive baseball practice improves the Go/Nogo reaction time, but not the simple reaction time. *Cognitive Brain Research, 22*, 257–264.

Kioumourtzoglou, E., Kourtessis, T., Michalopoulou, M., & Derri, V. (1998). Difference in several perceptual abilities between experts and novices in basketball, volleyball and water-polo. *Perceptual and Motor Skills, 86*, 899–912.

Kokubu, M., Ando, S., Kida, N., & Oda, S. (2006). Interference effects between saccadic and key-press reaction times of volleyball players and nonathletes. *Perceptual and Motor Skills, 103*, 709–716.

Kubo, K., Kanehisa, H., Ito, M., & Fukunaga, T. (2001). Effects of isometric training on the elasticity of human tendon structures in vivo. *Journal of Applied Physiology, 91*, 26–32.

Lee, J. W., Kin, S. J., & Song, Y. (2010). Visual search patterns and reaction movement in Taekwondo according to expertise. *Journal of Sports & Exercise Psychology, 32*, S99–S100.

Mausour, S., Maisetti, O., Cornu, C., & Portero, P. (2005). Lateral specificity in knee muscle function in competitive high jumpers compared with untrained individuals. *Isokinetics and Exercise Science, 13*, 27–37.

McKinley, P. A., & Pedotti, A. (1992). Motor strategies in landing from a jump: the role of skill in task execution. *Experimental Brain Research, 90*, 427–440.

Medbø, J. I., Jebens, E., Vikne, H., Refsnes, P. E., & Gramvik, P. (2001). Effect of strenuous strength training on the Na-K pump concentration in skeletal muscle of well-trained men. *European Journal of Applied Physiology, 84*, 148–154.

Mero, A., Jaakkola, L., & Komi, P. V. (1989). Neuromuscular, metabolic and hormonal profiles of young tennis players and untrained boys. *Journal of Sports Sciences, 7*, 95–100.

Mori, S., Ohtani, Y., & Imanaka, K. (2002). Reaction times and anticipatory skills of karate athletes. *Human Movement Science, 21*, 213–230.

Müller, S., Abernethy, B., Eid, M., McBean, R., & Rose, M. (2010). Expertise and the spatio-temporal characteristics of anticipatory information pick-p from complex movement patterns. *Perception, 39*, 745–760.

Nakamoto, H., & Mori, S. (2008). Sport-specific decision-making in a Go/Nogo reaction task: difference among nonathletes and baseball and basketball players. *Perceptual Motor Skills, 106*, 163–170.

Nelson, R. M., & Hunt, G. C. (1981). Strength-duration curve: intrarater and interrater reliability. *Physical Therapy, 61*, 894–897.

Paillard, T., Noe, F., Riviere, T., Marion, V., Montoya, R., & Dupui, P. (2006). Postural performance and strategy in the unipedal stance of soccer players at difference levels of competition. *Journal of Athletic Training, 41*, 172–176.

Ripoll, H., Kerlirzin, Y., Stein, J. F., & Reine, B. (1995). Analysis of information-processing, decision-making, and visual strategies in complex problem-solving sport situation. *Human Movement Science, 14*, 325–349.

Rivner, M. H., Swift, T. T., & Malik, K. (2001). Influence of age and height on nerve conduction. *Muscle and Nerve, 24*, 1134–1141.

Robertson, V., Ward, A., Low, J., & Reed, A. (2006). *Electrotherapy explained principles and practice*. Edinburgh, NY: Elsevier Butterworth Heinemann.

Schmidt, R. A., & Lee, T. D. (1999). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics.

Song, K. Y., & An, J. D. (2004). Premotor and motor reaction time of educable mentally retarded youths in a taekwondo program. *Perceptual and Motor Skills, 99*, 711–723.

Tsokovic, N. N., Blessing, D., & Williford, H. N. (2002). Physiological profile of recreational male and female novice and experienced Tae Kwon Do practitioners. *Journal of Sports Medicine and Physical Fitness, 44*, 164–172.

Wong, Y. M., Chan, S. T., Tang, K. W., & Ng, G. Y. F. (2009). Two modes of weight training programs and patellar stabilization. *Journal of Athletic Training, 44*, 264–271.

WTF. (2009). *WTF rules and regulations 2009*. WTF Web. http://www.wtf.org/wtf_eng/site/rules/file/20090203_Rules_and_Regulations_of_the_WTF_as_of_February_3_2009.pdf.

Yavuz, S. U., Sendemir-Urkmez, A., & Turke, r. K. S. (2010). Effect of gender, age, fatigue and contraction level on electromechanical delay. *Clinical Neurophysiology, 122*, 1700–1706.

Yerdelen, D., Uysal, H., Koc, F., & Sarica, Y. (2006). Effects of sex and age on strength–duration properties. *Clinical Neurophysiology, 117*, 2069–2072.

Zhou, S., McKenna, M. J., Lawson, D. L., Morrison, W. E., & Fairweather, I. (1996). Effect of fatigue and sprint training on electromechanical delay of knee extensor muscles. *European Journal of Applied Physiology, 72*, 410–416.

Zhou, S. (1995) Electromechanical delay in weight lifters and endurance trained athletes. *XVth Congress of the International Society of Biomechanics*. Jyvaskyla, Finland. P. 1036–1037.