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增強式跳躍訓練之跳箱訓練的下肢生物力學分析
Biomechanical Analysis of Lower Limbs during Plyometric Exercise – Box Jump

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中文摘要

增強式運動是一種常見的訓練方式用來增加運動員的爆發力與運動表現，近年來，這種運動方式也常常被拿來作為傷後運動員在重返運動場之前的復健方式。本篇研究的目的是比較增強式運動之中的兩種跳箱訓練(跨越跳箱與跳上跳箱)以及探討不同跳躍速度下(每分鐘 60 下、75 下與 90 下)對於強度與人體的影響。實驗的受試者是 12 名國立台灣體育運動大學田徑校隊的健康男性運動員。我們使用三維動作分析系統與兩塊測力板來收集在跳箱跳躍過程中的下肢運動學與動力學參數。結果顯示跳上跳箱的這種方式比跨越跳箱的方式在最大膝關節屈曲角度的時候有較多的髖關節與膝關節屈曲角度、較長的到達最大膝關節屈曲角度的時間以及能提供前十字韌帶較高的穩定度。在跳躍速度方面，每分鐘 90 下的速度能夠產生比較小的髖關節內收角度、膝關節外翻角度與較小的膝關節內/外翻力矩以及內/外旋力矩。

Abstract

Plyometric exercise is widely used as a training program for competitive athletes to increase their explosive power and to improve their performance. Also, it is getting popular to be used as a therapeutic exercise for post-injured athletes to help them to return to sports. The purpose of this study was to compare two plyometric box jumps (cross the box and front the box) and to investigate the effect of different jumping speeds (60 bpm, 75 bpm and 90 bpm) toward the intensity and human body. Twelve healthy, male athletes were recruited from track and field team in National Taiwan University of Physical Education and Sport. Kinematics and kinetics data of lower extremities were collected via three-dimensional motion analysis system and two force plateforms during the box jumping tasks under three different rates. We found that front the box (FB) had more hip and knee flexion at the checkpoint of maximum knee flexion, more time to maximum keen flexion and better ACL stabilization than cross the box (CB). While 90 bpm had less hip adduction, knee valgus and knee valgus/varus moments as well as internal/external rotation moments. According to our finding, we suggest that FB and 90 bpm are more suitable to be included in the training protocol for post-injured athletes in the return to sport phase of rehabilitation.

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Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Preface

Improving performance is one of the most important things for athletes and there are many studies confirmed that plyometric exercises could effectively elevate explosive power as well as enhance the performances for athletes in the competitions. Recently, there are also getting more focuses on plyometric exercise as a therapeutic program for high-level athletes on the return-to-sports phase of rehabilitation. It is not difficult to understand why the plyometric exercises are getting popular as a means of therapeutic programs for post-injured competitive athletes in the return-to-sports phase of rehabilitation because it is unlikely for them to adapt the excessive stress and the demanding intensity in return-to-play if they cannot cope with what the plyometric exercises would impose upon them.

According to the properties of the plyometric exercise – multiple repetitions, high impacts, high intensities and high loadings, this form of exercise helps athletes to enhance jumping performance, increase explosive power, increase concentric velocity and improve agility (Toumi, Best, Martin & Poumarat, 2004). However, the demands of the exercise also lead to high risk of injuries if the athletes didn’t meet the criteria before implementing plyometric exercise into their training programs (Chu, 1998; Hreljac et al., 2000; Potach & Chu, 2000) and let alone for post-injured athletes. In this case, the protocols, intensity, and the volume of the plyometric exercise should be designed and chosen more carefully in order to benefit from the adaptations and effects of the exercise and, at the same time, to minimize the potential risks during the training sessions.

The criteria of return-to-play include full range of motion (ROM), pain-free movement, and a certain level of muscle strength needed in the following activities (Saal, 1991). The training protocols emphasized in this phase are undoubtedly sport-specific that plyometric exercise and agility training are usually included. Plyometric exercise is defined as the muscles perform a quick eccentric contraction before doing the concentric contraction (Chu & Plummer, 1984), while agility training involves movements with quick changing directions, sudden stopping/starting and twisting (Fitzgerald, Childs, Ridge & Irrgang, 2002). There are also many studies proved that a combination of plyometric exercise and resistance training is more effective in lower extremity strengthening, tissue adaptation and injury reduction than any other forms of training alone (Mclaughlin et al., 2001).

Although plyometric exercises are widely utilized in various training regimens for performance improvement or rehabilitation, there is still no formulated way to clarify the determination of the intensity as in resistance/weight training. Therefore, quantifying plyometric exercise becomes an important issue for researchers in this field. In the previous studies, Jensen and Ebben (2005) evaluated the intensity of eight different plyometric exercises through measuring impulse, rate of eccentric force development (ERFD), ground reaction force (GRF), and knee joint reaction forces. The plyometric exercises in their study consisted of drop jumps (DJ) from 46cm and 61cm in height, pike jump, tuck jump, single leg jump, countermovement jump, squat jump and squat jump with 30% 1 RM. Another intensity of plyometric exercise was graded in Ebben's experiment (2008) by comparing the recruitments of quadriceps through electromyography (EMG). In 1998, Chu suggested that the intensity of different plyometric jumps were classified according to the effort involved in a task. The intensity for jump training exercises, under his classification, from low to high were jump-in-place, standing jump, multiple jumps and hops, box drills and depth jumps; however, there were no detail descriptions on each jump. In the meanwhile, he also addressed that the numbers of foot contact could be used as a standard for training volume, but that was also a general principle. Therefore, the method to quantify the intensity as well as the volume and to determine the combinations of the plyometric exercises for both condition training and the return-to-sport phase of rehabilitation remain some space to discuss.

Previous researches had shown that the less the foot contact time spent, the more the explosive power and vertical jump performance obtained, but still, there were no quantification of foot contact time and rate (Horita et al., 2002; Bobbert et al., 2004). The basic components of plyometric exercise are countermovement jump, horizontal jump and depth jump; therefore, previous studies had analyzed the biomechanical parameters of these jumps in order to evaluate the sport performance before and after the intervention of plyometric exercise (Verhoshanski, 1969; Verhoshanski & Tatyan, 1983; Hewett et al., 1996; Adams, 1984; Holcomb et al., 1996). However, the studies of the box drills were relatively rare.

Providing box drill was considered as a more complex plyometric exercise according to the intensity rank suggested by Chu (1998), the limited research on this topic evoked our interest to analyze certain biomechanical parameters of this form of jump to investigate the effect of different box jumps. The setting of the box jumps in the current study was based on Chu’s pyramiding box hops (1998). The jump description of Chu’s pyramiding box hops was entitled as front the box (FB) in this study, and another similar jump which was more like the jump description of Houglum’s multiple jumps and hops (2001) was entitled as cross the box (CB) in this study.

Speed was suggested to be a means to adjust the intensity of plyometric exercises (Houglum, 2001). Normally, athletes were instructed to complete the movements as fast as they could in this form of exercise. Therefore, in this study, different rates – 60 bpm, 75 bpm and 90 bpm were set to represent different speeds in order to investigate how the different speeds affect the human body and the intensity.

1.2 Purpose

The purpose of this study was to compare two box jumps and to investigate the effect of different jumping speeds toward the intensity and human body by analyzing the biomechanical parameters of two box jumps (cross the box and front the box) and three different rates (60 bpm, 75 bpm and 90 bpm).

Chapter 2 Literature Review

2.1 Introduction of Plyometric exercise

Plyometrics was originated from Europe simply referring to jump training. In the early 1970s, it was widely noticed according to the splendid performance of athletes from Eastern Europe in the sports of track and field, gymnastics, and weight lifting, for whom jumping exercises were implemented in their training programs. However, the term of plyometrics was firstly coined by an American track and field coach named Fred Wilt. Its Greek origins, plio versus metric, meant measurable enhancement (Houglum, 2001; Chu, 1992). Plyometric exercises then rapidly became popular to trainers and athletes for producing explosive power by linking force and speed together; it was considered to be essential to be included in the training protocols especially for athletes playing in jumping, weight lifting and throwing (Chu, 1992).

The ultimate goal of plyometric exercises is to increase output of explosive power. Its mechanism was based on the reaction of mechanical and neurological components in neuromuscular system responding to the stress (Houglum, 2001). As for mechanical components, they could be divided into contractile elements and non-contractile elements.

Contractile elements are myofibrils, while non-contractile elements were referred to series elastic component (SEC) and parallel elastic component (PEC) according to their arrangements. Tendons and sheath were the main contributions of SEC and muscle's connective tissues were classified as PEC. In the Stretch- Shortening Cycle (SSC), non-contractile elements were deemed to be an important factor to power production due to their elastic property. As for the neurological components, muscle spindles and Golgi tendon organs play important roles in power output by activating the stretch reflex of muscle spindles and decreasing the inhibition from Golgi tendon organs. Therefore, plyometric exercise could be described as a means with the property of a quick eccentric movement followed by the forceful concentric contraction to increase muscle strength and explosive power (Houglum, 2001; Chu, 1998).

There are three distinct phases in plyometric exercises: eccentric phase, amortization phase, concentric phase (Houglum, 2001). In the eccentric phase, muscle is lengthened by a rapid stretch. Its mechanism is due to muscle spindle is very sensitive to a sudden change in length of the muscle – the faster the rate of the stretch, the greater the amount of the response. This is the most important phase during plyometric exercises since they could increase the stimulation to facilitate greater response of muscle spindles and then provide greater muscle activities. Amortization phase is referred to the transition from eccentric phase to concentric phase. The amount of time of this phase should be kept short; otherwise the elastic energy gained from the last phase would be dissipated as heat and wasted. Also, the prolonged time in this phase would inhibit stretch reflex since the time and the force production are inversely related. Concentric phase is the outcome of the combined effect from eccentric phase and amortization phase. The desired explosive power would be produced in concentric phase if both eccentric phase and amortization phase could occur rapidly in a very short time. By integrating the mechanical and neurological components in neuromuscular system, plyometric exercises could bridge the gap between muscle strength and forceful power output to improve sport performance (Wilt, 1975).

There are various types of plyometric exercises in lower extremities: jumps-in-place, standing jumps, multiple jumps and hops, box jumps and depth jumps (Figure 2.1-1 to Figure 2.1-5) (Houglum, 2001).

Jumps-in-place (Figure 2.1-1) are repeated jumps that involve jumping in the same place from the beginning to the end. The intensity is adjustable from low to high. Jumps-in-place with low intensity are useful activities for establishing a short amortization phase and at the same time, jump techniques could also be developed if these kinds of jumps relate to the specific sports (Houglum, 2001).

Figure 2.1-1. Jumps-in-place
Note. From *Therapeutic Exercise for Athletic Injuries* (p.299), by P. A. Houglum, 2001, Champaign, IL: Human Kinetics. Copyright 2001 by Peggy A. Houglum.

Standing jumps (Figure 2.1-2) are single jumps that put emphasis on maximal effort for each exertion; therefore the recovery time between jumps is exceptionally crucial. The direction of its motion could be either horizontal or vertical. The intensity could progress by adding barriers such as cones and advance by including sprint immediately after landing (Houglum, 2001).

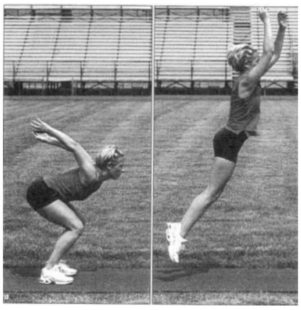

Figure 2.1-2. Standing jumps

Note. From *Therapeutic Exercise for Athletic Injuries* (p.300), by P. A. Houglum, 2001, Champaign, IL: Human Kinetics. Copyright 2001 by Peggy A. Houglum.

Multiple jumps and hops (Figure 2.1-3) require the skills from both jumps-in-place and standing jumps. These types of jumps address on maximal attempts without resting between repetitions. The intensity could be modified by performing the jumps with one or two legs, with or without barriers, in a single or multiple directions (Houglum, 2001).

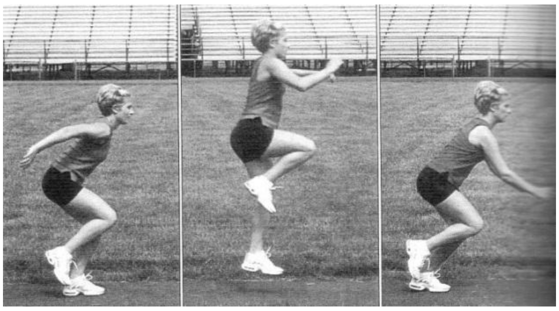

Figure 2.1-3. Multiple jumps and hops

Note. From *Therapeutic Exercise for Athletic Injuries* (p.302), by P. A. Houglum, 2001, Champaign, IL: Human Kinetics. Copyright 2001 by Peggy A. Houglum.

Box jumps (Figure 2.1-4) involve jumps and hops on and off boxes with various heights that they require more advanced skills from multiple jumps and hops. The directions include both vertical and horizontal jumps. The intensity depends on the box height. The number of the box could be set from one to five (Houglum, 2001; Chu, 1998).

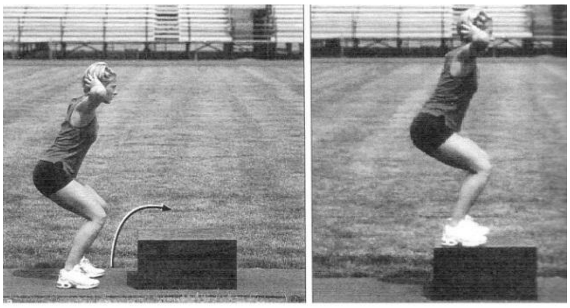

Figure 2.1-4. Box jumps
Note. From *Therapeutic Exercise for Athletic Injuries* (p.306), by P. A. Houglum, 2001, Champaign, IL: Human Kinetics. Copyright 2001 by Peggy A. Houglum.

Depth jumps (Figure 2.1-5) are considered to be the most aggressive jumps among all because subject’s own weight and the acceleration of gravity are involved additionally simultaneously. The movement description of these kind of jumps is first to step off the box, second drop on the ground, third jump upward off the ground immediately with maximal exertion. There is one thing should be kept in mind that the first move is to step off the box instead of jump off the box therefore extra stresses could be avoided. The intensity could be progressed by landing and jumping with single leg, increasing box height and box numbers (Houglum, 2001).

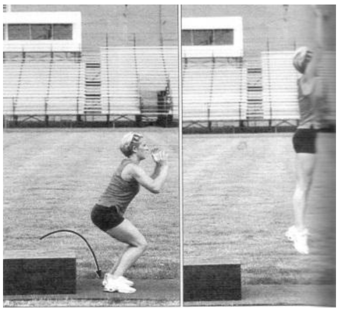

Figure 2.1-5. Depth jumps

Note. From *Therapeutic Exercise for Athletic Injuries* (p.308), by P. A. Houglum, 2001, Champaign, IL: Human Kinetics. Copyright 2001 by Peggy A. Houglum.

2.2 Training Plan of Plyometric exercise

Before implementing plyometric exercise into training protocols, there are three prerequisite parameters need to be noted; they are strength, flexibility, and proprioception (Houglum, 2001; Chu, 1998).

According to the definition of power – rate of work production, that can also be expressed as the product of force and velocity; greater force would produce greater power which is the reason why muscle strength is regarded as the foundation of the plyometric exercises. Enough strength could assure better quality of the movement control required in the plyometric exercises and also it could reduce the incidence of injuries from overuse. Besides, while the difficulty of the plyometric exercises progresses, the greater strength may be needed. Another benefit from strengthening is that the hypertrophied muscles provide additional elastic elements in the eccentric phase due to their increased cross sections to provide greater strength. Submaximal plyometric exercises such as skipping could be applied at the first beginning; however, the minimum strength required for the plyometric exercises depends on the severity on demand (Houglum, 2001). Squat with 60 % body weight five times within five seconds was recommended by Chu (1998) for more demanding plyometric exercises in lower extremities.

Power generated from concentric phase also relies on the amounts of lengthening of the muscles during the eccentric phase of plyometric exercises. Therefore, muscles with better flexibility allow better degree of lengthening and then result in greater power production. Besides, muscles with good flexibility not only provide full ROM needed for activities but also provide a better level of force absorption in plyometric exercises that were known as exercises with high impacts and stresses (Houglum, 2001).

Proprioception is referred to the ability of body to transmit position sense as well as kinesthesia, to discriminate the information and then to respond to the stimulation consciously or unconsciously to regulate the posture or movement of the body appropriately. Good athletic skills rely on good proprioception and proprioception could also be presented as agility, balance and coordination (Houglum, 2001). Therefore, it is not so hard to understand that why a certain degree of agility, balance and coordination is required in plyometric exercises to adequately perform controlled forceful and rapid movements. Although different severity and complexity of plyometric exercises require different levels of control, agility, balance and coordination are needed in all levels of plyometric activities. For this reason, any types of plyometric exercises should be avoided before basic static and dynamic proprioception could be acquired. (Houglum, 2001;

Zamani, Rahnama, Khayambashi, & Lenjannezhad, 2010).

As to design plyometric programme, there are four variables could be manipulated; they are intensity, volume, frequency and recovery (Houglum, 2001; Chu, 1998; Allerheiligen & Rogers, 1995).

Intensity is the degree of effort involved in doing an exercise or the stress of the given task. In plyometric exercises, intensity could be adjusted by changing the complexity of the task, adding weights during the task, increasing the speed of the task, raising the height of the boxes or increasing the distance covered (Houglum, 2001; Chu, 1998).

Volume is the total work executed in a single session. In lower extremities, the volume of the plyometric exercises is monitored by the numbers of foot contact in jumping tasks and by distance in bounding tasks during one session. In upper extremities, the volume of the plyometric exercises is measured by the numbers of repetition. The intensity and the goals would help to determine the appropriate volume selected in any plyometric exercise session (Houglum, 2001; Chu, 1998).

Frequency is the number of times/sessions that are taken place in a training cycle. Though it also depends on the intensity of the exercise and the tolerance of the individual, at least forty-eight hours between sessions is recommended (Houglum, 2001; Chu, 1998).

Recovery is referred to the quantity of resting time between sets or groupings of multiple exercises. It is the key factor to determine the plyometric exercises applied focus on developing the power or enhancing the muscular endurance (Houglum, 2001). Generally speaking, shorter resting time (10 to 15 seconds) between sets is used to promote muscular endurance, while longer resting time (45 to 60 seconds) between sets is used to improve power (Chu,1998). Accordingly, a work to rest ratio of 1:5 to 1:10 was suggested to assure the intensity of the exercise and the adequate performance (Chu, 1998).

There are some other issues need to be considered before starting plyometric exercises as they are normally more intense than other forms of exercise programs. These issues include age, body weight, competitive level, surface, foot wear, technique, progression, goals (Houglum, 2001; Chu, 1998; Allerheiligen & Rogers, 1995).

Plyometric exercises should be applied carefully on children and youth (8 to 13 years old) due to their physical immaturity – their bones and muscles are not strong enough to bear the stress and the mechanism of their proprioceptive feedback is not fully mature yet to cope with the intense activities. Thus, the volume and the intensity of the plyometric exercises should be kept low. The general guideline is that moderate to high intensity should be avoided for those under the age of sixteen (Houglum, 2001).

Plyometric exercises are activities of high impact, so naturally they would impose more stress on joints and tendons. For those whose body weight is 100Kg or above could not perform the same plyometric exercises as those who with lighter body weight due to safety consideration (Allerheiligen & Rogers, 1995).

Competitive level determines the training level of plyometric exercises applied in the therapeutic programs. That is to say all the therapeutic programs should involve a certain level of plyometric exercises, however, moderate- to high- level plyometric exercises are likely to be executed on those who participate in competitive sports while the same intensity level for competitive athletes may not be required for those who with recreational purpose (Houglum, 2001).

The proper surface for implementing plyometric exercises is that neither too hard nor too soft, and with the ability to absorb some of the impacts come from plyometric tasks. The appropriate surface, for example, Resilite mats are good for the indoor activities and grass is good for the outdoor exercises. Harder surface like concrete should be avoided because of the higher impact forces. The reason why softer surface is not very adequate is that it would result in reducing the elastic property needed in plyometric exercises (Houglum, 2001; Chu, 1998). Shoes with good cushion and support are the best footwear for plyometric exercises. Again, if the shoe is too spongy, it would cause the instability at landing and take-off during the activities, thus a good execution would be restricted (Houglum, 2001).

Proper technique is very important for performing plyometric exercises. It is suggested to land with midfoot and then push-off with the ball of foot in order to decrease the impacts and to reduce the amortization phase. Trunk should be kept straight so forces could be transmitted and the contribution of arms could be utilized. The quality of the performance needs to be monitored and fatigue should be prevented; in this way, undesired movements, bad habits and risk of injury during the plyometric exercises could be minimized (Houglum, 2001). The progression depends on individual's physical condition and the adaptations to the stress. Lower level tasks should be accomplished before moving to the next stage. The means of progression include adjusting the intensity, resting time and the duration of the given tasks (Houglum, 2001). Goal settings are determined by individual's condition and the sport participation. They should also be evaluated and re-evaluated by individual's performance to match their progressions. While the current goals are achieved, new goals should be established (Houglum, 2001).

2.3 Adaptations after Plyometric exercise

There were many previous studies proved that after the intervention of plyometric exercises, various significant improvements in lower extremities could be observed including motor strategies, motor controls, joint stability, sport injury prevention and anaerobic power output.

As for motor strategies and motor controls, motor strategies learnt in plyometric programs could be reproduced during the activities, such as quadriceps-hamstrings co-activation and adductors pre-activation to provide knee stability (Chimera et al., 2004). Also, implementing plyometric exercises into the regular endurance training programs of some triathletes who were suffering from the aberrant neuromotor control during running after cycling could hold a positive outcome in correcting the aberrance (Bonacci, 2011).

Knee and ankle injuries were common to see in sport field; however, previous studies showed that both of the joints could benefit from plyometric exercises in various ways. Chimera et al. (2004) suggested that knee stability could be increased after the intervention of plyometric exercises. Heweet et al. (1996) found that after implementing plyometric exercises into a training program could efficiently decrease the impact forces during landing and could reduce adduction/abduction torque of the knee joint to lessen the incidence of non-contact ACL injury in female athletes. There were also meaningful changes found in Lower Extremity Functional Scale, Knee Outcome Survey, agility test, vertical jump performance, and 40-yard sprint test after the intervention of both plyometric and agility trainings for patient with post-surgical anterior knee pain in a case report (Newberry & Bishop, 2006). A knee proprioception assessment was conducted by Zamani et al. in 2010 by asking subjects to reproduce three fixed knee angles and by using Biodex isokinetic dynamometer to calculate the proprioception senses; significant improvements were observed in the group that included an eight-week plyometric training. Ismail et al. (2010) investigated the effect of both plyometric exercises and resistive exercises for athletes after inversion ankle sprain. They found that functional performance was better improved in plyometric group than in resistive group after six week respective training.

One of the most important effects desired after the intervention of plyometric exercises is the explosive power which was proved to be enhanced by Luebbers et al. (2003). However, according to their findings, the sufficient time of recovery should be applied to the trainings with high volumes and short sessions, otherwise the desired optimal performance would be affected.

2.4 Plyometric exercise & Resistance training

Anterior cruciate ligament (ACL) injury is not uncommon for athletes in sport field. Therefore, there are various ACL prevention programs established in order to reduce the risk of the injuries. Normally, ACL prevention programs are the combinations of several training protocols such as flexibility exercise, resistance training, balance training, agility training and plyometric exercise. The training protocols mentioned above were proved to be effective in decreasing the incidence of ACL injury (Rozzi et al., 1999; Caraffa et al., 1996). However, there seemed to be a tendency for the researchers to compare the effects of plyometric exercise versus resistance training before and after the interventions via investigating their changes in neuromuscular and biomechanical characteristics.

As for the difference between plyometric exercise and resistance training, several variables were always discussed in previous studies such as the incidence of non-contact ACL injury, quadriceps strength, hamstrings torque, joint angles of hip flexion and knee flexion during landing, pre-activation of hip abductor , co-activation of hip adductor and abductor, and ground reaction force (GRF).

Non-contact ACL injury was claimed to be reduced in both plyometric exercise and resistance training. Lehnhard et al. (1996) declared that athletes could benefit from regular strengthening to decrease the incidence of ACL injury. Hewett et al. (1996) also suggested after the intervention of plyometric exercise for eight weeks, non-contact ACL injury of female athletes would be reduced.

As for quadriceps strength and hamstring torque, significant improvements of quadriceps strength were both found in plyometric exercise and resistance training (Lephart et al., 2005). However, hamstrings torque was only found ameliorated after plyometric intervention (Hewett et al., 1996).

Joint angles of hip flexion and knee flexion during landing task were thought to be an important variable to assess because joint forces during the landing task could be attenuated and hamstrings would also be tensioned to protect ACL with the additional posterior force (Renstrom et al.,1986; Hirokawa et al.,1991). Lephart et al. (2005) suggested that the desired increase of hip flexion and knee flexion during the jump-landing task could be observed in both plyometric and basic resistance groups.

The activations of hip adductor/abductor were only found in plyometric group (Lephart et al., 2005). The preparatory activation of gluteus medius was observed before landing in his study, thus, thigh was thought to be positioned in advance to cope with the impact forces at landing which may lead to inappropriate hip adduction and knee valgus (Zeller et al., 2003; Ferber et al., 2003). Similar, the increase of early co-activation of hip adductor and abductor was reported in Chimera's study (2004) after a six-week intervention of plyometric exercises.

In addition, both Hewett et al. (1996) and Irmischer et al. (2004) reported that a reduction of ground reaction force (GRF) was observed after including plyometric exercises into training protocols. For the standpoint of injury prevention, it is important to decrease vertical GRF during jump-landing task due to the notion that the less impact forces upon the joints, the lower onsets of the injuries.

2.5 Clinical application of Plyometric exercise

Plyometric exercises were first used to enhance explosive power and improve sport performance for uninjured athletes, and yet in recent years, they are usually cooperated into rehabilitation programs for post-injured athletes in order to help them safely return to sports participations. The traditional therapeutic exercises address more on the treatments of the early stage after injury, for example it is strongly recommended to start with a relatively slower speed, to begin with lower forces and to initiate movements at single planes in order to facilitate desired neuromuscular recruitment, to regain full ROM, to increase muscle strength and to enhance muscle endurance (Kannus Parkkari & Jarvinen, 2003; Saal, 1991); however, those could hardly simulate the real demands of forces, speed, movements and techniques required in athletic competitions. Therefore, plyometric exercise could be regarded as a crucial training protocol to be included in the therapeutic exercises for those who need to return to athletic competitions or high-demanding activities; furthermore, it could also be used as a means to evaluate that if the athletes are ready to return to play (Newberry & Bishop, 2006; Gregory et l., 2008).

Another important thing to keep in mind is even the lowest intensity of plyometric exercises should be avoided in several occasions, for example, the early stage of rehabilitation, the acute stage after injury or the stage of consisting pain and remaining joint instability (Wilk et al., 1993). It is very crucial for participants to obtain a certain muscle strength, flexibility, proprioception and neuromuscular control before implementing plyometric exercises as a part of rehabilitation programs. Generally speaking, it is applied in the late stage of rehabilitation and should be combined with sport-specific trainings.

Chapter 3 Material and Methods

3.1 Subjects

Twelve healthy, male athletes were recruited from track and field team in National Taiwan University of Physical Education and Sport. Their specialties were high jump and long jump. Subjects reported no history of serious knee injury or other lower extremity trauma within 6 months. All subjects participated in nationally or locally organized track and field competitions and they had regular training programs including weight training, endurance, speed, agility and plyometric exercise. This study was approved by the Research Ethics Committee of the Central Regional Research Ethics Center (Appendix C) and all the subjects provided written informed consent (Appendix B) prior to their participations. All of them were able to follow the instructions and complete the movements demanded in this experiment without any problem. The basic information of these twelve subjects in this study was shown in Table 3.1.

Table 3.1.

Subject information (Mean ± SD)

Age (y/o)	Height (cm)	Body mass (Kg)	Track & field experience (year)
21±2	178±8	70±6	9±4

3.2 Experimental Instrumentation

VICON motion analysis system, two Kistler force plateforms were used for data collection in this study. The laboratory setting was shown in Figure 3.2-1.

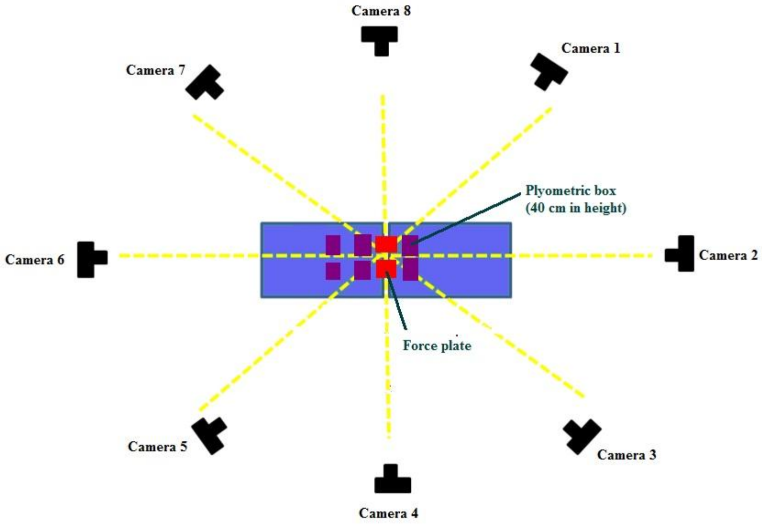

Figure 3.2-1. Laboratory setting

3.2.1 Motion analysis system

VICON motion analysis system (Oxford Metrics LID. UK) (Figure 3.2-2) with eight high-speed optical cameras (Figure 3.2-2) was used to collect kinematical data.

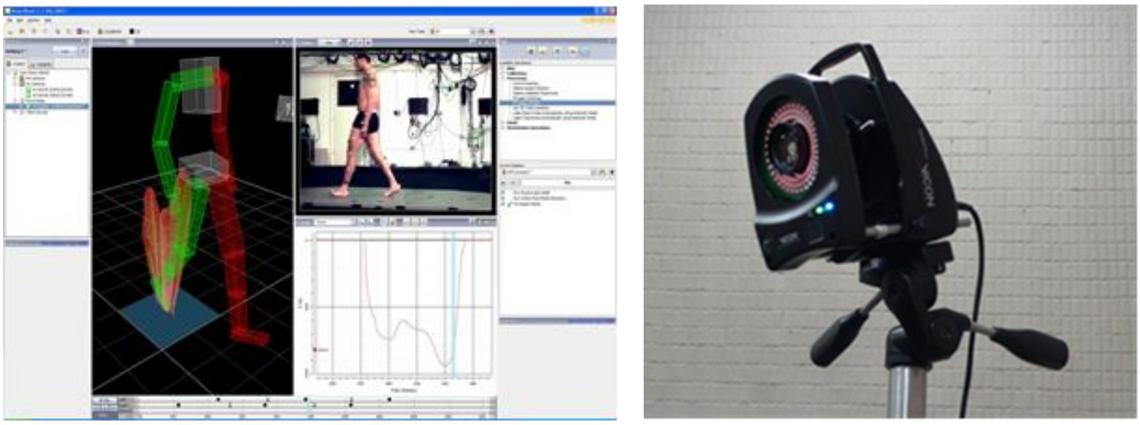

Figure 3.2-2. VICON motion analysis system

3.2.2 Force plateform

Kinetic data were collected using two Kistler force plateforms (Type 9260AA6, Swiss) (Figure 3.2-3).

Figure 3.2-3. Kistler force plateform

3.2.3 Plyometric box

The heights of the plyometric boxes in this study were 20 cm, 30 cm and 40 cm respectively, nonslip surfaces were attached on the top of the boxes. Width x length was 30 cm x 40 cm for each box. The gaps between two boxes of same heights were 5.5 cm and the distances between two boxes of different heights were 62.5 cm (Figure 3.2-4).

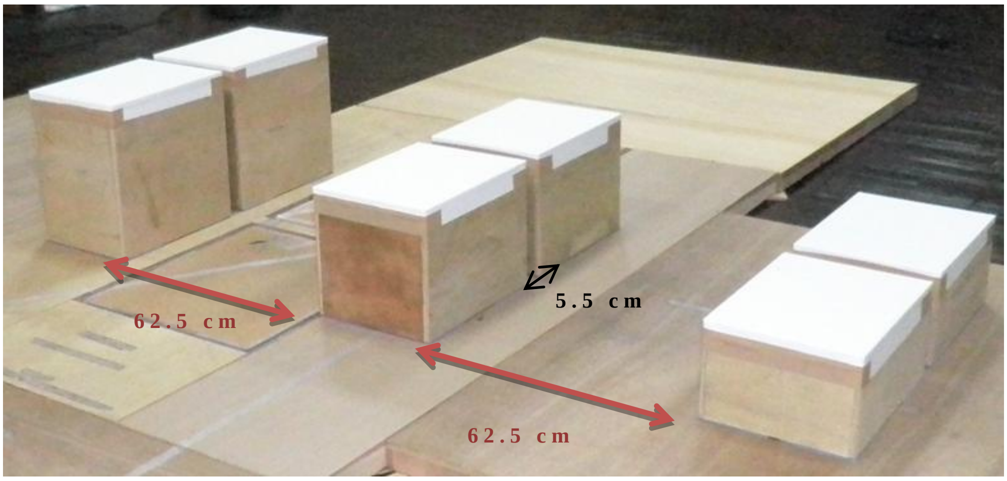

Figure 3.2-4. Plyometric box

3.3 Experimental Procedures

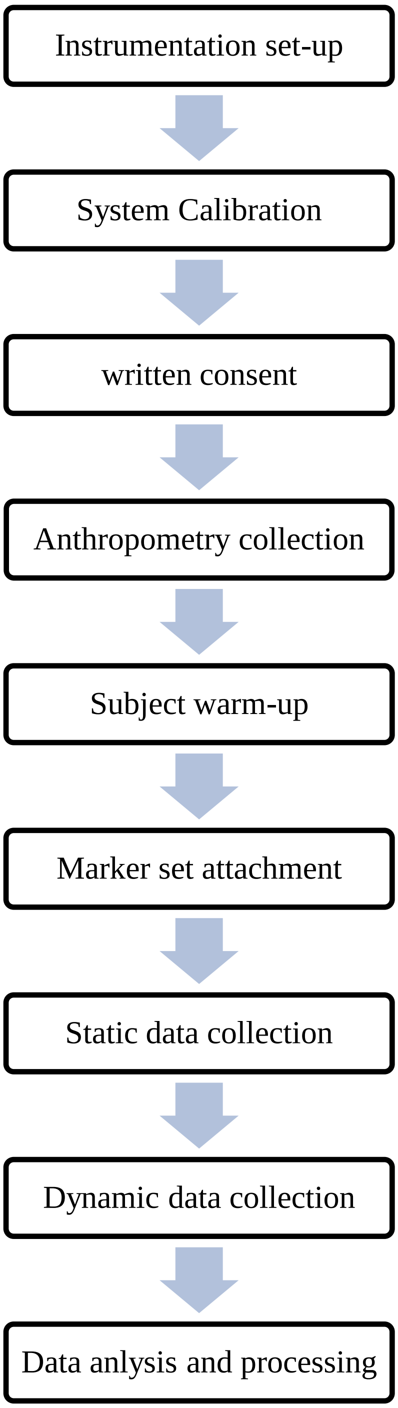

Figure 3.3-1. Experimental procedures

3.3.1 Instrumentation set-up

Eight high speed optical cameras were set surrounded two Kistler force plateforms. The sampling rate of the high speed cameras was 250 Hz that the three-dimensional trajectories of the marker sets on the subject could be captured. And all the markers should be captured by at least two cameras. VICON NEXUS software was utilized to label the markers and process the data collected.

Two Kistler force plateforms were set between 30 cm and 40 cm boxes bilaterally. Ground reaction forces and moments were sampled at a rate of 1000 Hz during plyometric box jump.

3.3.2 System Calibration

A wand (Figure 3.3-2) was used to calibrate the capture volume and the error correction of the cameras. An L-frame (Figure 3.3-3) was set to define the laboratory coordinate system.

Figure 3.3-2. Wand

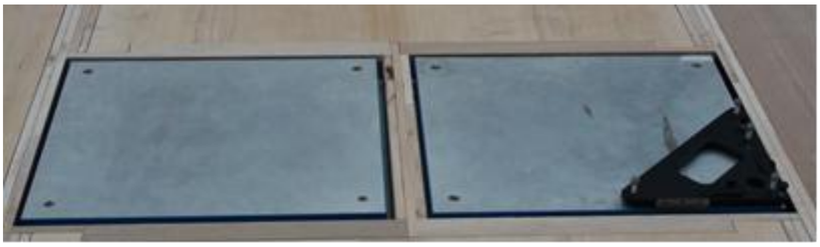

Figure 3.3-3. L-frame

3.3.3 Collection of Anthropometric data

Linear and circumferential anthropometric measurements of each subject were recorded before the experiment for later data processing (Appendix A). The segments we measured including upper arms, forearms, torso, pelvis, thighs and lower legs.

3.3.4 Warm-up

Each subject had 5 to 10 minutes to warm up which was arranged to reduce the risk of injury and to decrease the fatigue during the plyometric box jumps performed in the experiment. The warm-up exercises contained light flexibility exercises such as light stretching of flexors and extensors in hip, knee and ankle joint, and included light skipping and bouncing.

3.3.5 Marker set attachment

The marker set was attached on the anatomical landmarks of the subjects to represent the three-dimensional trajectory of each body segment. The markers were placed on the anatomical landmarks modified from Helen Hayes (Table 3.3-1).

Table 3.3-1.

Marker set attachments

Anatomical landmarks		L/ R side	Note
Pelvis	ASIS	L & R	-
	PSIS	L & R	-
	Sacrum	-	Share the same horizontal plane with ASIS and PSIS.
L/E	GT	L & R	-
	Medial knee	L & R	-
	Lateral knee	L & R	-
	Medial malleolus	L & R	-
	Lateral malleolus	L & R	-
	2nd metatarsal	L & R	-
	Calcaneus	L & R	Share the same horizontal plane with 2nd metatarsal.

Note. L/E: Lower extremity, ASIS: Anterior superior iliac spine, PSIS: Posterior superior iliac spine, GT: Greater Trochanter, Medial knee: Medial epicondyle of femur, Lateral knee: Lateral epicondyle of femur. L: Left, R: Right.

3.3.6 Data collection of neutral posture

Subject stood statically with the neutral position.

Articulation centers and relative distances collected between joints in this stage could be used as the basic information for calculation in dynamic data analysis and as the reference for dynamic movements.

3.3.7 Dynamic data collection

The jumping rates of this study were 60 bpm, 75 bpm and 90 bpm respectively. The subjects were first standing with feet shoulder-width apart and then instructed to jump cross the box (CB) (Figure 3.3-4) or front the box (FB) (Figure 3.3-5) with the rates mentioned above in a randomized order. CB referred to the subjects jump over the box that there were only three foot contacts while completing the jump; this form of jump was similar to multiple jumps and hops described by Houglum (2001). FB meant subjects jump up to the box and down to the ground consecutively for three times; this form of jump was based on the pyramiding box hops described by Chu (1998). There were six sets of box jumps with corresponding rates and each set contained three trials. Subjects had at least two minutes break between sets to prevent fatigue. Plyometric boxes and force plates were placed bilaterally as shown on Figure 3.3-6.

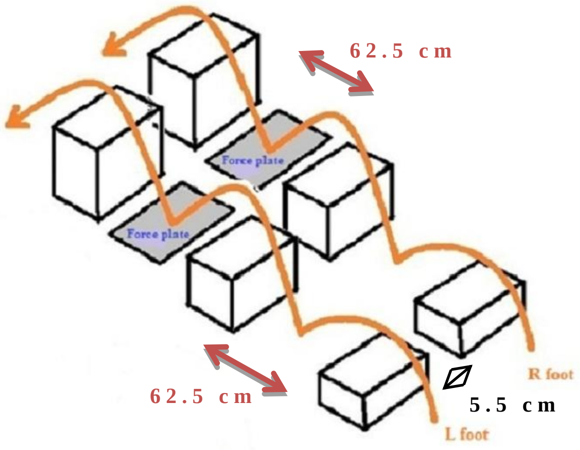

Figure 3.3-4. Cross the box

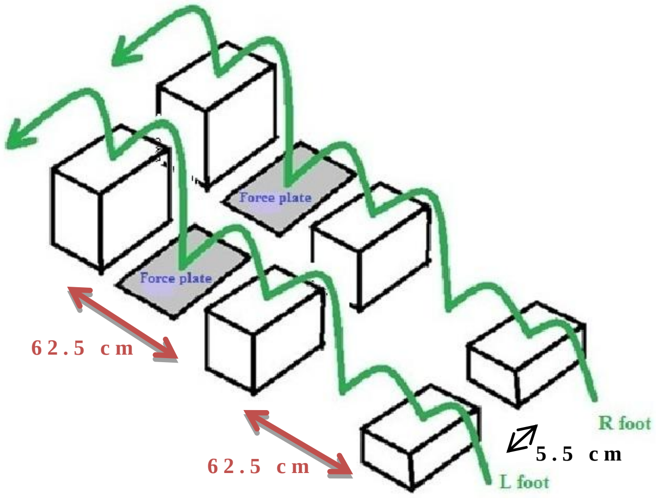

Figure 3.3-5. Front the box

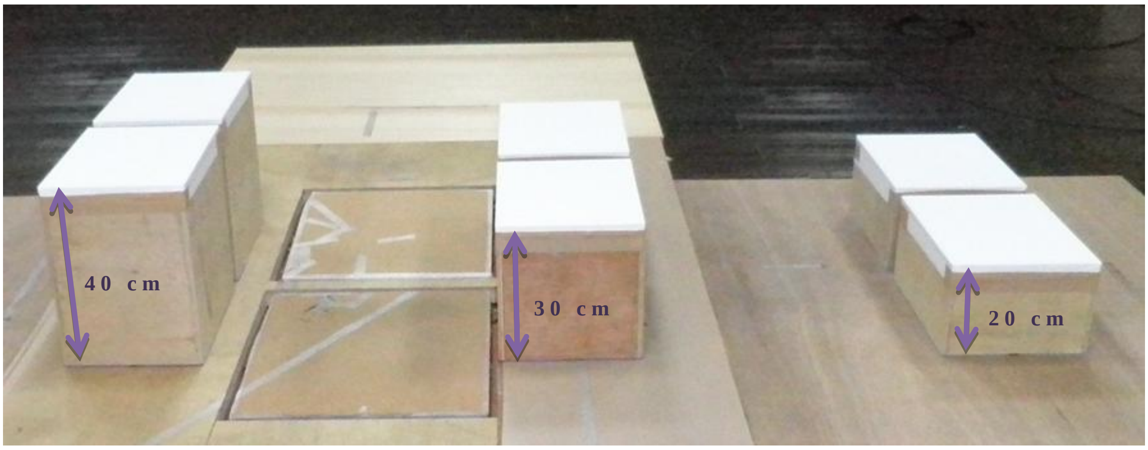

Figure 3.3-6. Plyometric boxes and force plateforms

3.3.8 Data processing and analysis

Human segments were assumed to be the rigid body in this study. High speed cameras were set to capture the three-dimensional trajectories of the reflective markers in space and the coordinate system of all the segments would be defined. The trajectories of the reflective markers were smoothed by 6 Hz low pass filter through generalized cross-validation spline smoothing route (Woltring, 1986). Joint centers could be marked and calculated by the reflective markers attached on subjects. Real position of the mass center for each segment could be deducted by Anthropometry measurements and relative position of mass centers for each segment (de Leva, 1996), so the acceleration of center of gravity and Euler parameters of each segment in the laboratory coordinate system would then be obtained. Joint angles could be calculated by Euler angle and the rotatory orientation was defined as following: flexion/extension (y) - abduction/adduction (x’) - internal rotation/external rotation (z”). The mass of each segment and the moment of inertia of each segment were calculated by McConville formula (1980). Joint forces and joint moments were obtained by newton-Euler equation through inverse dynamic methods.

As for joint Kinematics and Kinetics, the second jump was extracted from one complete box jump to represent the Kinematics and Kinetics patterns. It could be divided into five checkpoints by the lines of the time frames on horizontal axis. These checkpoints were (1)landing, (2)peak landing force, (3)maximum knee flexion, (4)take-off after landing, (5)last maximum jumping height. The joint angles of hip joint and knee joint at landing as well as maximum knee flexion were important indicators for researchers to speculate the amounts of impact forces attenuation upon joints. Peak landing force and time to peak landing force were parameters for rate of force development calculation. Time to maximum knee flexion was also an indicator to speculate the impact force absorption for the joints. The time from landing to take-off was the total foot contact which was an important factor for researchers to evaluate the effect of stretch-shortening cycle (SSC).

3.3.9 Statistical analysis

Data were analyzed with SPSS 12.0. Two-way (2 box jumps x 3 velocities) repeated measures ANOVA were performed to access the differences in kinetic and kinematical parameters. Statistical significance of $p < .05$ was set.

Chapter 4 Results

In this study, we assume that box jumping is a symmetrical movement. In this case, ROM, joint forces and joint moments are considered to be equal bilaterally during box jump, therefore the following results presented are the biomechanical analysis of the data from subjects' dominant legs which were declared to be right.

4.1 Joint Kinematics & Kinetics during Different Box Jumps

The patterns of Kinematics and Kinetics during different box jumps were showed in Figure 4.1-1 to Figure 4.1-6.

In Figure 4.1-1, while performing CB, hip joint was about 30 degrees at landing and then the angle of flexion kept increased and reached its peak at the point of maximum knee flexion which was about 67 degrees. After that, hip joint started to extend to the checkpoint of take-off and after. At the point of last maximum jumping height, hip flexed around 71 degrees. Furthermore, hip joint remained slight abduction and external rotation throughout the jump. As for hip joint moment, between the checkpoints of landing and peak landing force, hip flexor reached its peak moment and hip extensor reached its peak moment at around 0.008 seconds after the checkpoint of peak landing force. Then hip extensor worked as the prime mover until the checkpoint of take-off. Hip abductor activated before landing but adductor worked between the checkpoint of landing and maximum knee flexion. After that, hip abductor activated again until the checkpoint of take-off. As for hip joint force, a great compression force took place right after the checkpoint of peak landing force. Also, there was a slight anterior shear force observed between the checkpoint of landing and peak landing force, while peak posterior shear force took place right after the checkpoint of peak landing force and then carried out to take-off. Peak medial shear force was noted as the point that peak posterior shear force occurred.

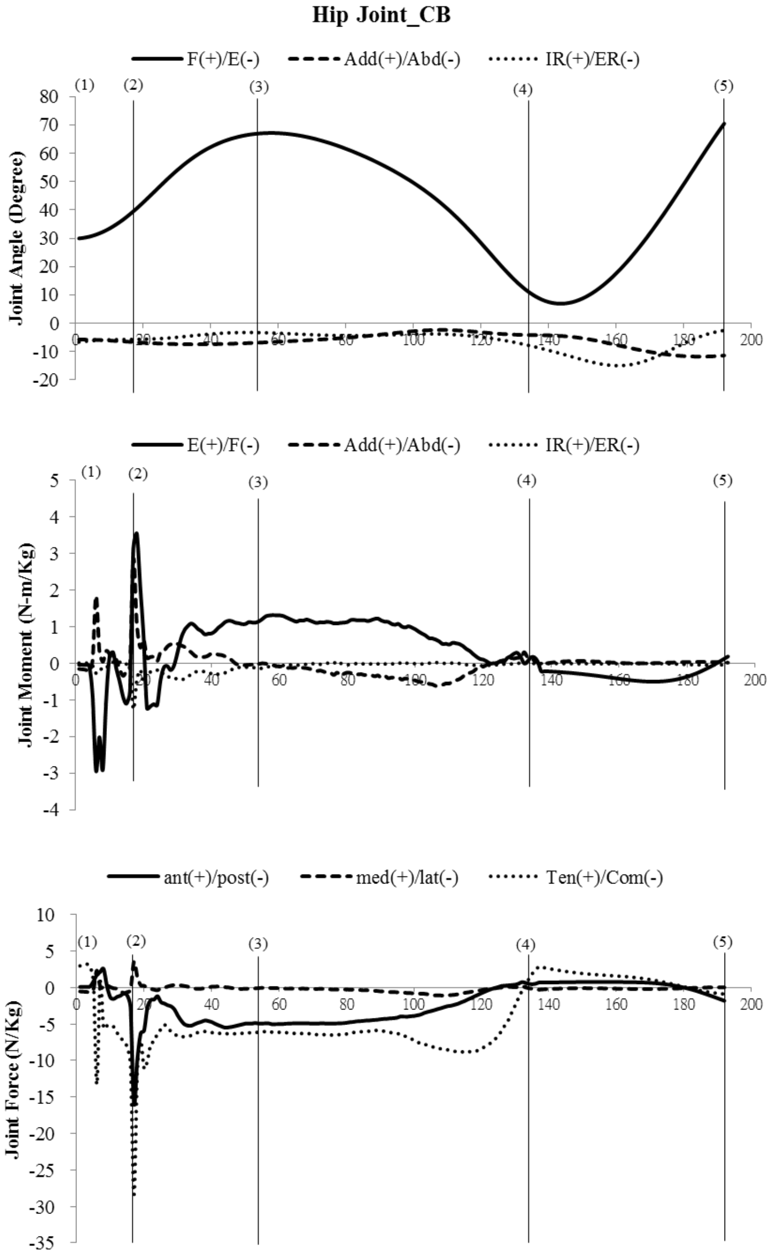

Figure 4.1-1. Hip joint angle, joint moment and joint force of cross the box (CB) during box jump.

Note. Checkpoints: (1)landing (2)peak landing force (3)maximum knee flexion (4)take-off after landing (5)last maximum jumping height.

In Figure 4.1-2, while performing FB, hip joint was about 20 degrees at landing and then the angle of flexion kept increased and reached its peak at the point of maximum knee flexion which was about 68 degrees. After that, hip joint extended to the checkpoint of take-off. At the point of last maximum jumping height, hip flexed around 12 degrees. Also, hip joint remained abduction and external rotation throughout the jump. As for hip joint moment, after 0.02 seconds of landing, hip flexor reached its peak moment and then hip extensor activated rapidly before the checkpoint of peak landing force. Hip flexor reached its second peak at 0.008 seconds after the checkpoint of peak landing force, then again hip extensor activated rapidly to its peak around 0.028 seconds after the checkpoint of peak landing force. After that, hip extensor worked until take-off. Hip abductor activated before landing but adductor worked through the jump. Hip external rotation moment was found through the same period of time. As for hip joint force, FB was like CB. A great compression force was notable right after the checkpoint of peak landing force. There was also a slight anterior shear force observed between the checkpoint of landing and peak landing force, while peak posterior shear force took place right after the checkpoint of peak landing force and then carried out to take-off. Peak medial shear force was noted as the point that peak posterior shear force occurred.

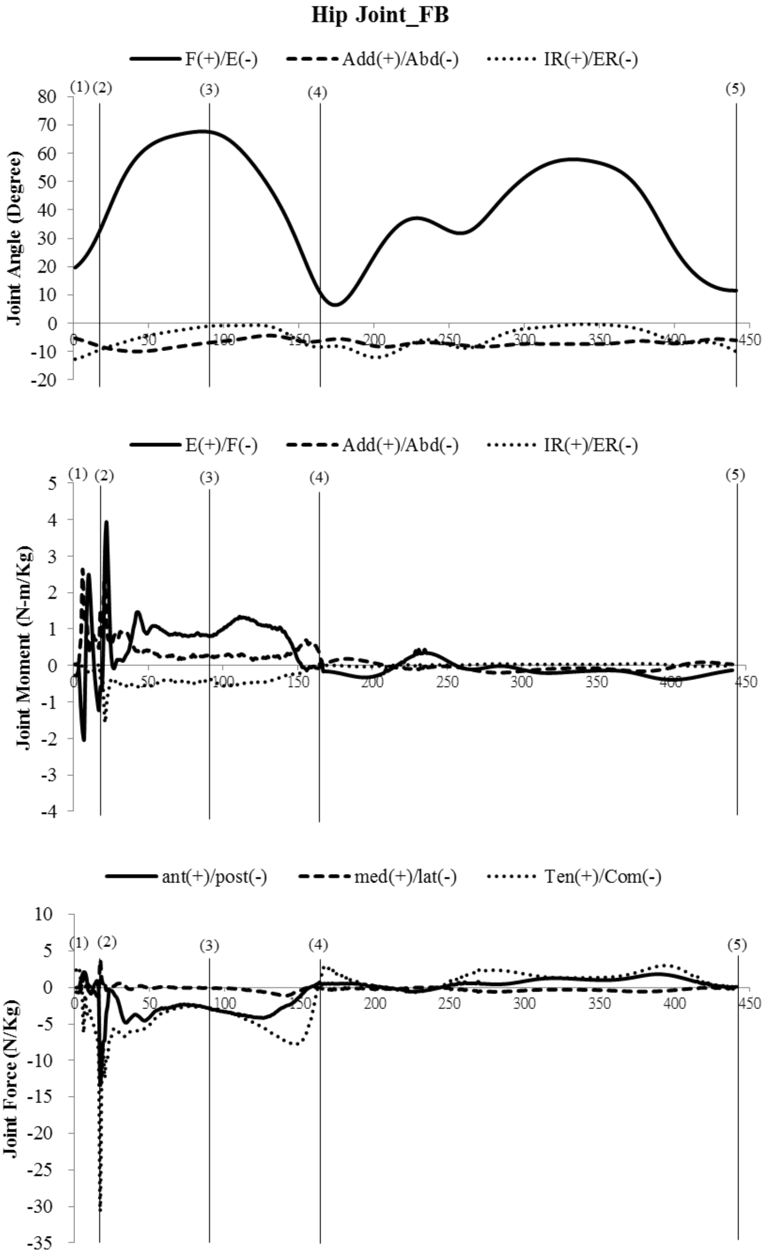

Figure 4.1-2. Hip joint angle, joint moment and joint force of front the box (FB) during box jump.

Note. Checkpoints: (1)landing (2)peak landing force (3)maximum knee flexion (4)take-off after landing (5)last maximum jumping height.

In Figure 4.1-3, while performing CB, knee flexion was around 23 degrees at landing and increased to its peak value of 76 degrees at the checkpoint of maximum knee flexion; after that knee then extended to the checkpoint of take-off. At the point of last maximum jumping height, knee flexed around 112 degrees. As for knee joint moment, the prime mover between landing and take-off was knee extensor. Knee adduction moment was found throughout the same period of time as knee extensor. And there was not much of internal/external rotation moment during the jump. As for knee joint force, a great compression force took place right after the checkpoint of peak landing force. The main joint force in knee joint during landing and take-off was the anterior shear force. Medial shear force also took place from landing to take-off.

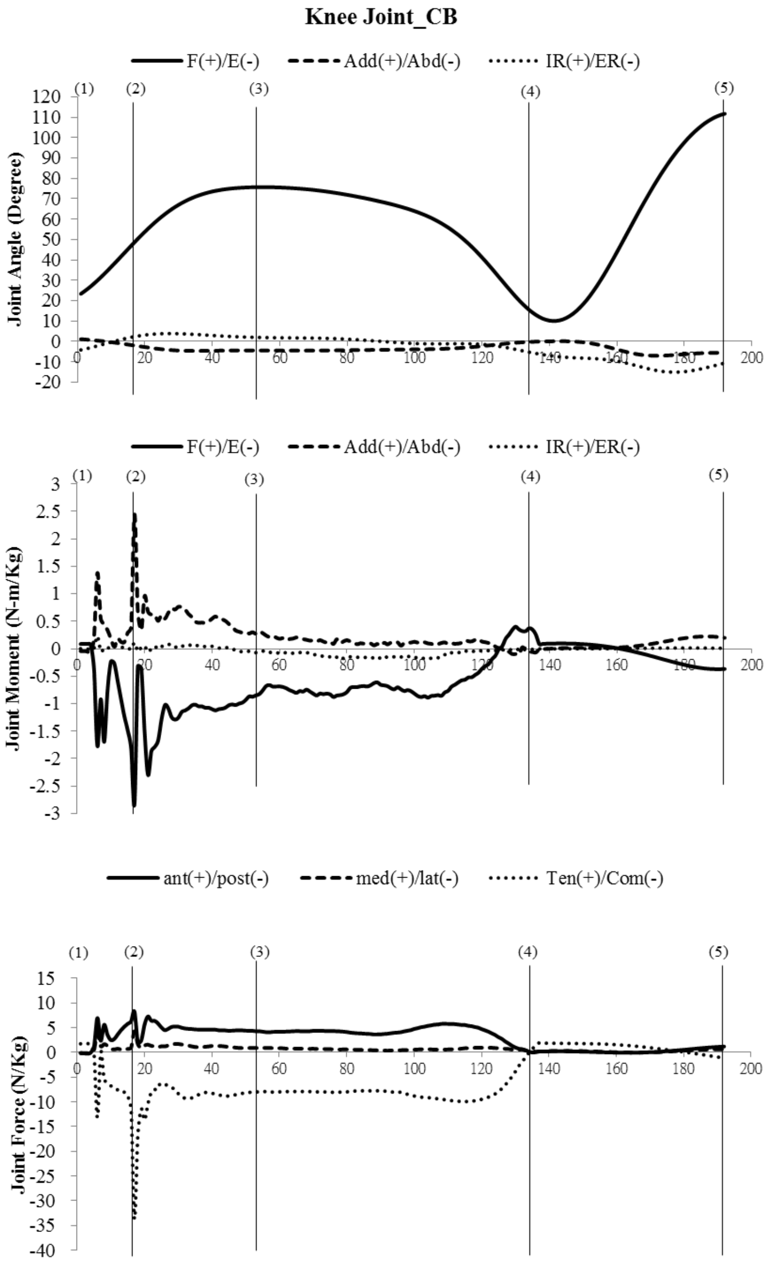

Figure 4.1-3. Knee joint angle, joint moment and joint force of cross the box (CB) during box jump.

Note. Checkpoints: (1)landing (2)peak landing force (3)maximum knee flexion (4)take-off after landing (5)last maximum jumping height.

In Figure 4.1-4, while performing FB, knee flexion was around 19 degrees at landing and increased to its peak value of 81 degrees at the checkpoint of maximum knee flexion; after that knee then extended to the checkpoint of take-off. At the point of last maximum jumping height, knee flexed around 30 degrees. As for knee joint moment, the prime mover between landing and take-off was knee extensor. However, between the checkpoints of landing and peak landing force, knee extensor activated right after landing, and then knee flexor took place rapidly after. After knee extensor reached its peak moment which is around 0.008 seconds after the checkpoint of peaking landing force, knee extensor activated throughout the jump until take-off. Knee adduction moment was notable from landing to take-off, and same as knee internal rotation moment. As for knee joint force, FB was similar to CB. A great compression force was found right after the checkpoint of peak landing force. Medial shear force took place from landing to take-off. Besides, the main joint force during landing and take-off was the anterior shear force.

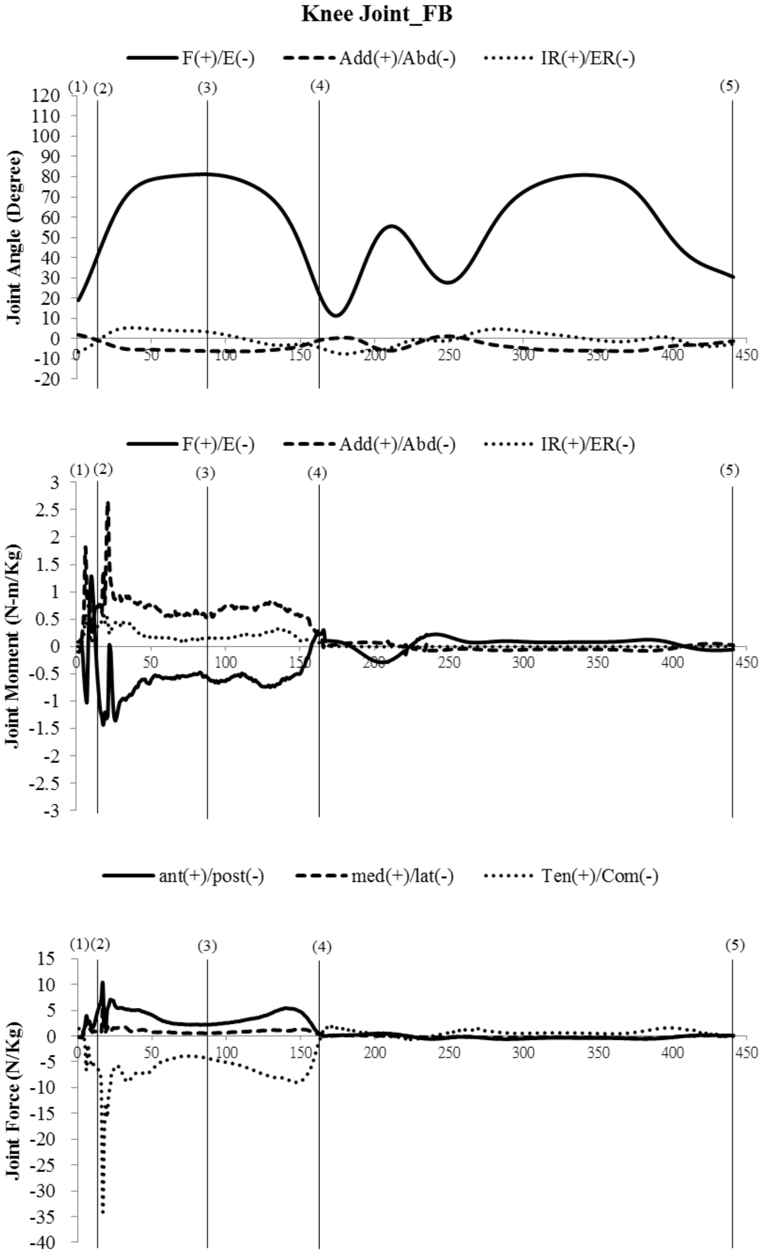

Figure 4.1-4. Knee joint angle, joint moment and joint force of front the box (FB) during box jump.

Note. Checkpoints: (1)landing (2)peak landing force (3)maximum knee flexion (4)take-off after landing (5)last maximum jumping height.

In Figure 4.1-5, while performing CB, ankle joint landed with planar flexion 25 degrees which decreased through the foot contact on the force plate; dorsiflexion slightly increased after the point of maximum knee flexion, then plantar flexion increased again to the checkpoint of take-off and after. As for ankle joint moment, plantar flexor took place from landing to take-off. Ankle invertor activated before the check point of maximum knee flexion, and ankle evertor took over after that. Ankle external rotation moment was also noted from landing to take-off. As for ankle joint force, a great compression force was found right after the checkpoint of peak landing force. The main joint force in ankle joint during landing and take-off was the anterior shear force. And lateral shear force was notable around the checkpoint of peak landing force.

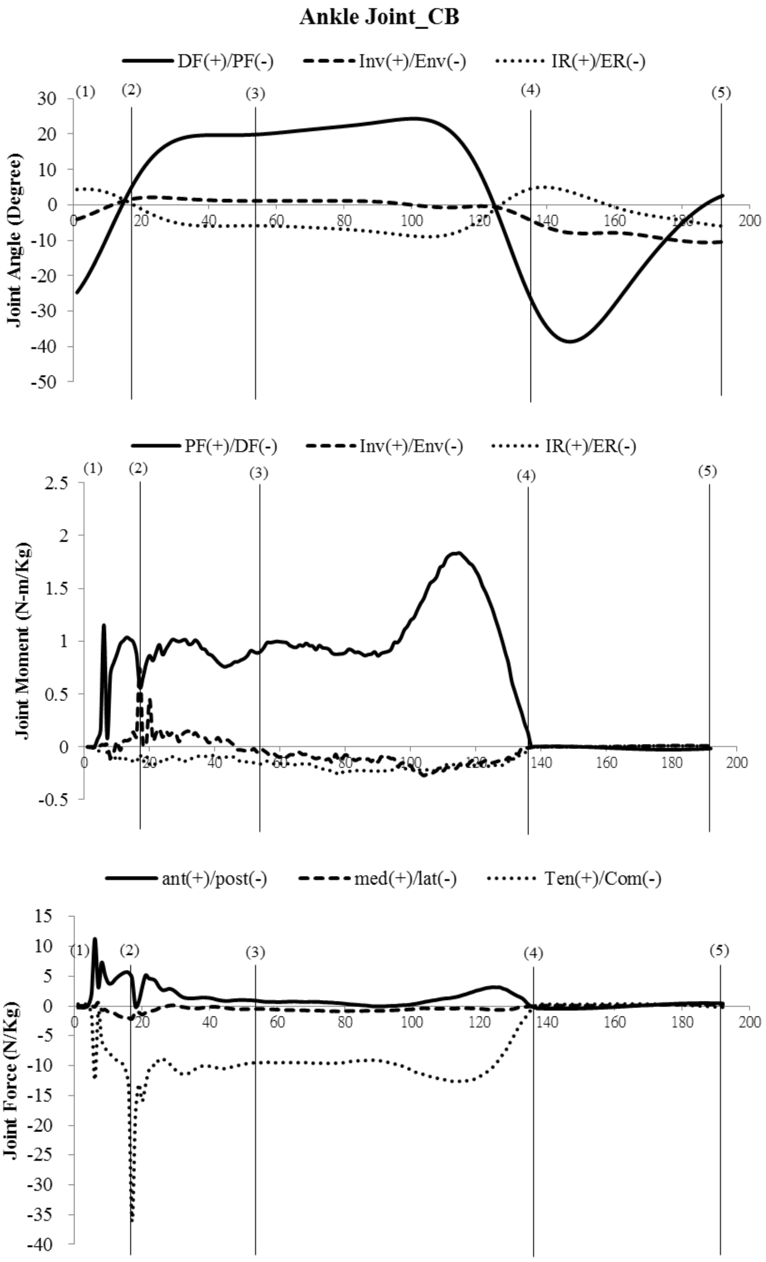

Figure 4.1-5. Ankle joint angle, joint moment and joint force of cross the box (CB) during box jump.

Note. Checkpoints: (1)landing (2)peak landing force (3)maximum knee flexion (4)take-off after landing (5)last maximum jumping height.

In Figure 4.1-6, while performing FB, ankle joint landed with planar flexion 24 degrees which decreased through the foot contact on the force plate; dorsiflexion slightly increased after the checkpoint of maximum knee flexion, then plantar flexion increased again to the checkpoint of take-off and after. As for ankle joint moment, plantar flexor took place from landing to take-off. Ankle plantar flexor reached to its first peak moment around 0.008 seconds after the checkpoint of peak landing force and reached to its second peak around 0.08 seconds before take-off respectively. Ankle invertor activated from landing to take-off. Ankle internal rotation moment was also noted from landing to take-off. As for ankle joint force, FB and CB were alike. A great compression force was notable right after the checkpoint of peak landing force. Lateral shear force was also found around the checkpoint of peak landing force. And the main joint force during landing and take-off was the anterior shear force.

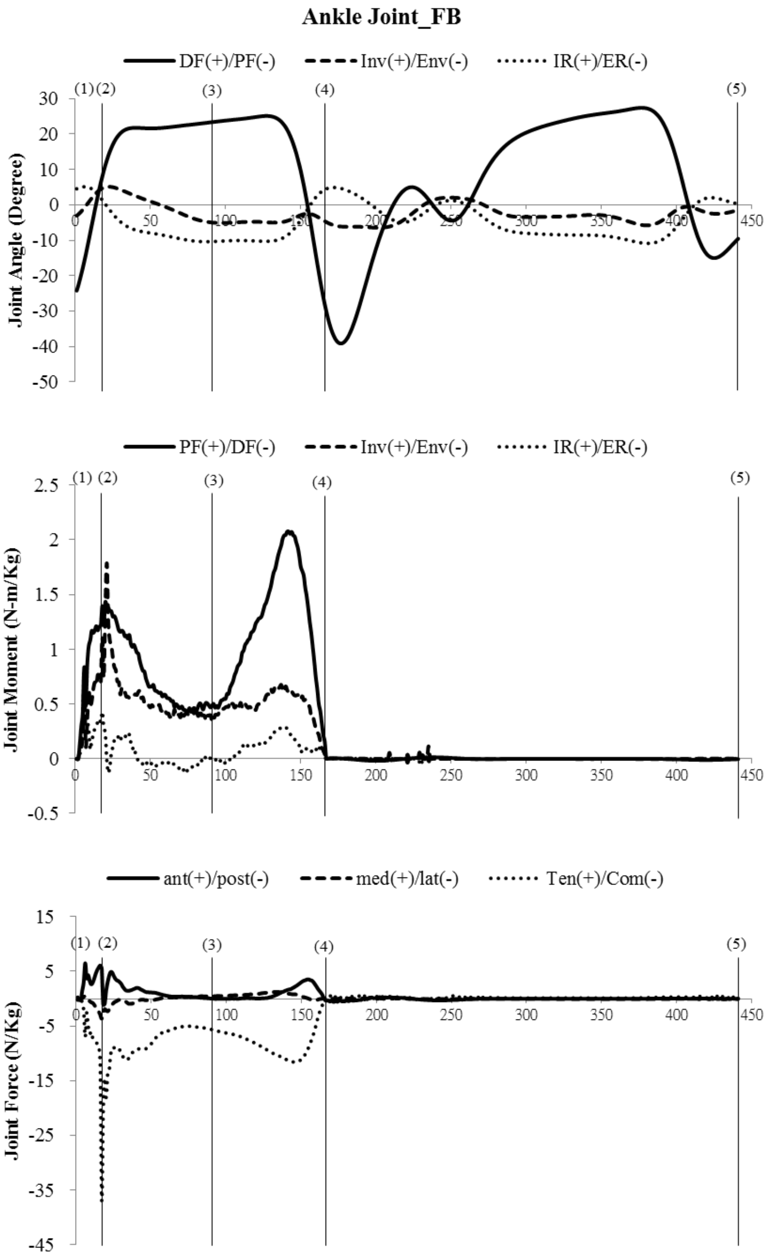

Figure 4.1-6. Ankle joint angle, joint moment and joint force of front the box (FB) during box jump.

Note. Checkpoints: (1)landing (2)peak landing force (3)maximum knee flexion (4)take-off after landing (5)last maximum jumping height.

The time parameter of the joint kinematics was also included in this study. Time to maximum knee flexion (Figure 4.1-7) and total foot contact time (Figure 4.1-8) were calculated. Although the subjects in the current study had to follow the rates instructed instead of their maximal exertions while performing box jumps, it still gave us a glimpse of how the different rates result in different foot contact time. Different box jumps were found no significant differences in time to maximum knee flexion under each rate; however, there was a tendency found for FB to hold longer time to maximum knee flexion than CB. As for total foot contact time, FB was greater than CB at the rate of 60 bpm and 75 bpm; however, when it comes to 90 bpm, two jumps showed no significant difference.

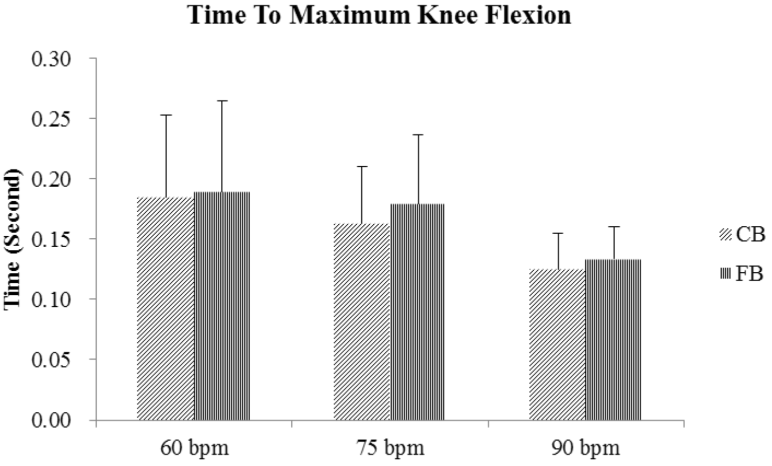

Figure 4.1-7. Time to maximum knee flexion of different box jumps under different rates.

Note. *p < .05. bpm: beat per minute, CB: cross the box, FB: front the box.

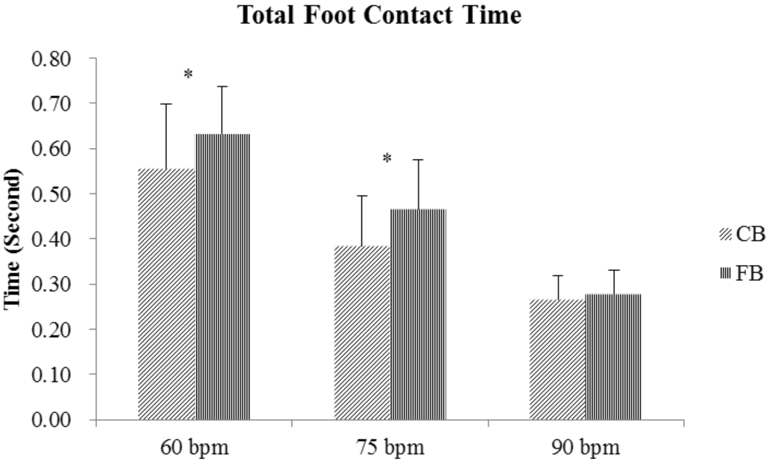

Figure 4.1-8. Total foot contact time of different box jumps under different rates.

Note. *p < .05. bpm: beat per minute, CB: cross the box, FB: front the box.

4.2 Joint Range of Motion (ROM) in Different Box Jumps

There were interaction effects between box jumps and rates in joint ROM of hip flexion/extension and ankle internal/external rotation (Figure 4.2-1). In different box jumps under different rates, the ROM of hip flexion/extension was found significantly greater in CB than in FB among all rates (60 bpm, 75 bpm and 90 bpm); however, only when it reached to 90 bpm could be found that ROM of ankle internal/external rotation was significantly lesser in CB than in FB (Figure 4.2-1). While in different rates under different box jumps, significant differences only appeared in FB instead of CB; the ROM of hip flexion/extension was found significantly greater in both 60 bpm and 75 bpm than in 90 bpm, while 60 bpm and 75 bpm had no significant difference. For the ROM of ankle internal/external rotation, which in both 60 bpm and 90 bpm were significantly greater than which in 75 bpm, though there was no significant difference found between 60 bpm and 90 bpm (Figure 4.2-1).

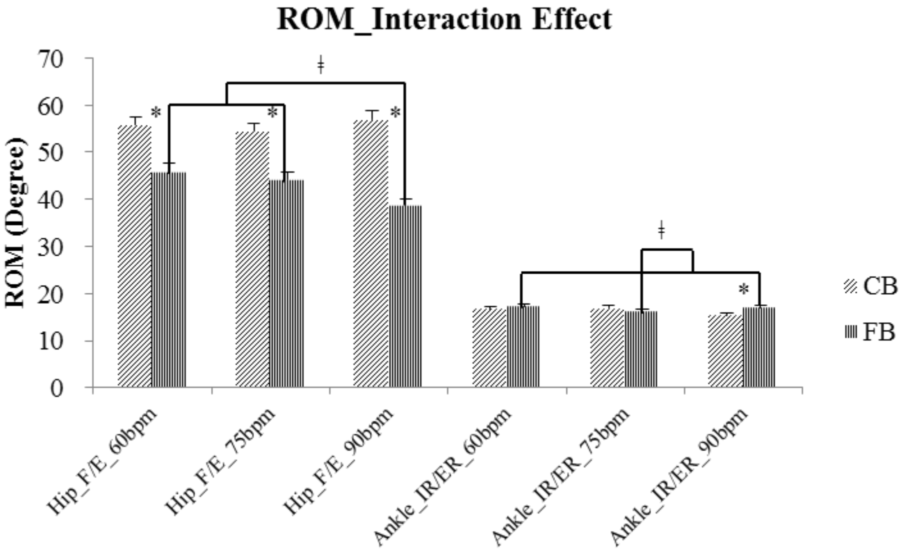

Figure 4.2-1. ROM - Interaction effect.

Note. *$p < .05$: significant difference between box jumps.

ǂ $p < .05$: significant difference among rates.

ROM: range of motion, CB: cross the box, FB: front the box, F/E: Flexion/Extension, IR/ER: Internal rotation/External rotation.

For non-interaction effects, significant differences of ROM were found in hip joint and knee joint while comparing different box jumps (Figure 4.2-2). In hip internal/external rotation, ROM in CB was lesser than in FB. And in both knee flexion/extension and adduction/abduction, ROM was found greater in CB than in FB (Figure 4.2-2). For different rates, significant differences of ROM were also found in hip joint and knee joint instead of ankle joint (Figure 4.2-2). In hip internal/external rotation, ROM in 75 bpm was greater than in 90 bpm. While in knee flexion/extension, adduction/abduction and internal/external rotation, ROM in 90 bpm seemed to be the least among all rates (Figure 4.2-2).

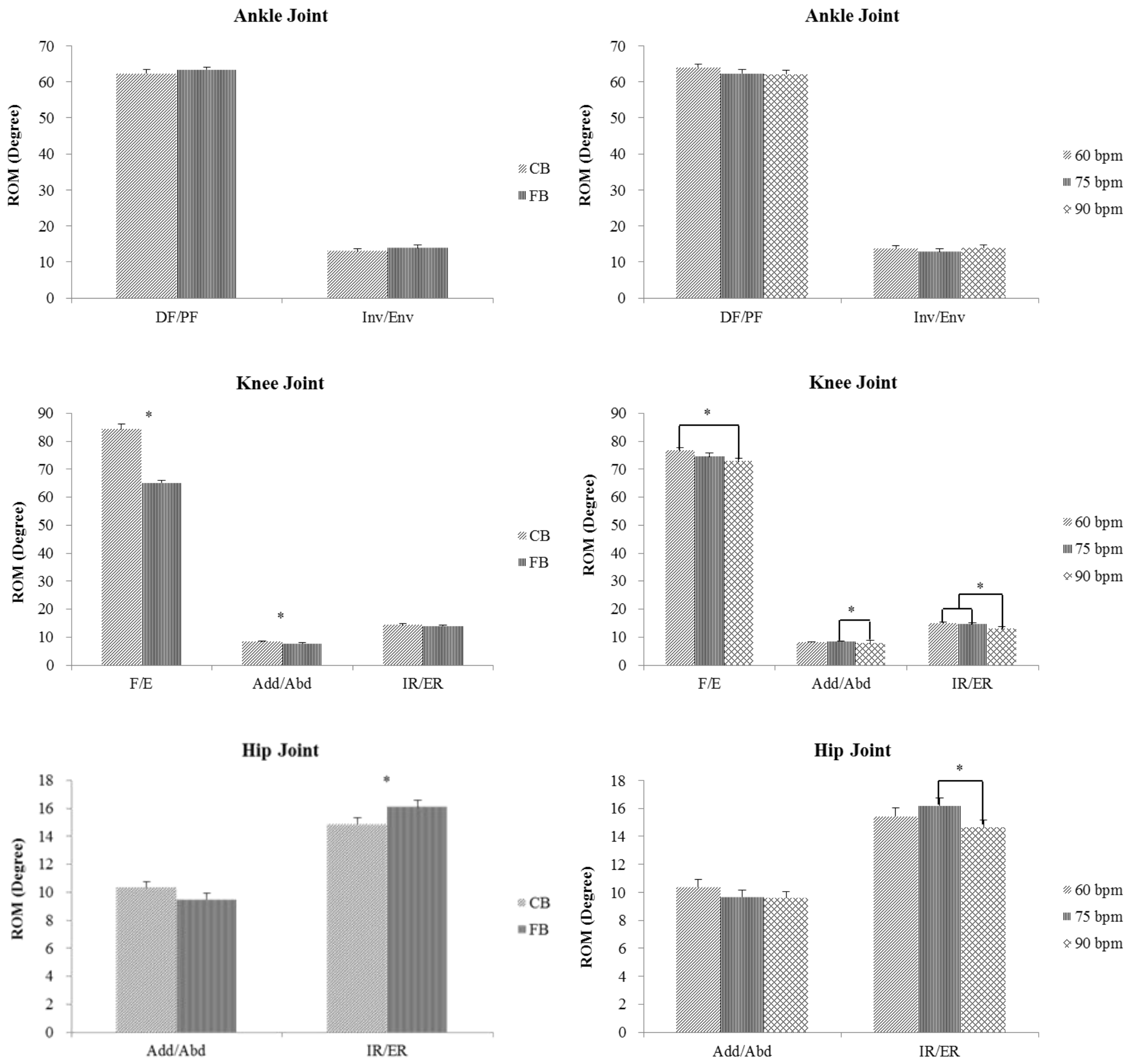

Figure 4.2-2. ROM - Non-interaction effect.

Note. *p < .05. ROM: range of motion.

F/E: Flexion/Extension, Add/Abd: Adduction/Abduction, IR/ER: Internal rotation/External rotation, DF/PF: Dorsiflexion/Plantar flexion, Inv/Env: Inversion/Eversion.

4.3 Peak Joint Forces in Different Box Jumps

There was no interaction effect between different box jumps and rates for peak joint forces in lower limbs (Figure 4.3). For peak joint forces of different box jumps, CB hold less anterior shear force in hip joint, posterior shear force in knee joint and posterior shear force in ankle joint than FB; however, for ankle anterior shear force, the result was opposite (Figure 4.3). As for peak joint forces in different rates, it was found the most in 90 bpm for knee anterior shear force, knee posterior shear force and ankle medial shear force; while for both hip anterior shear force and ankle anterior shear force, it was found the least in 90 bpm among all rates (Figure 4.3).

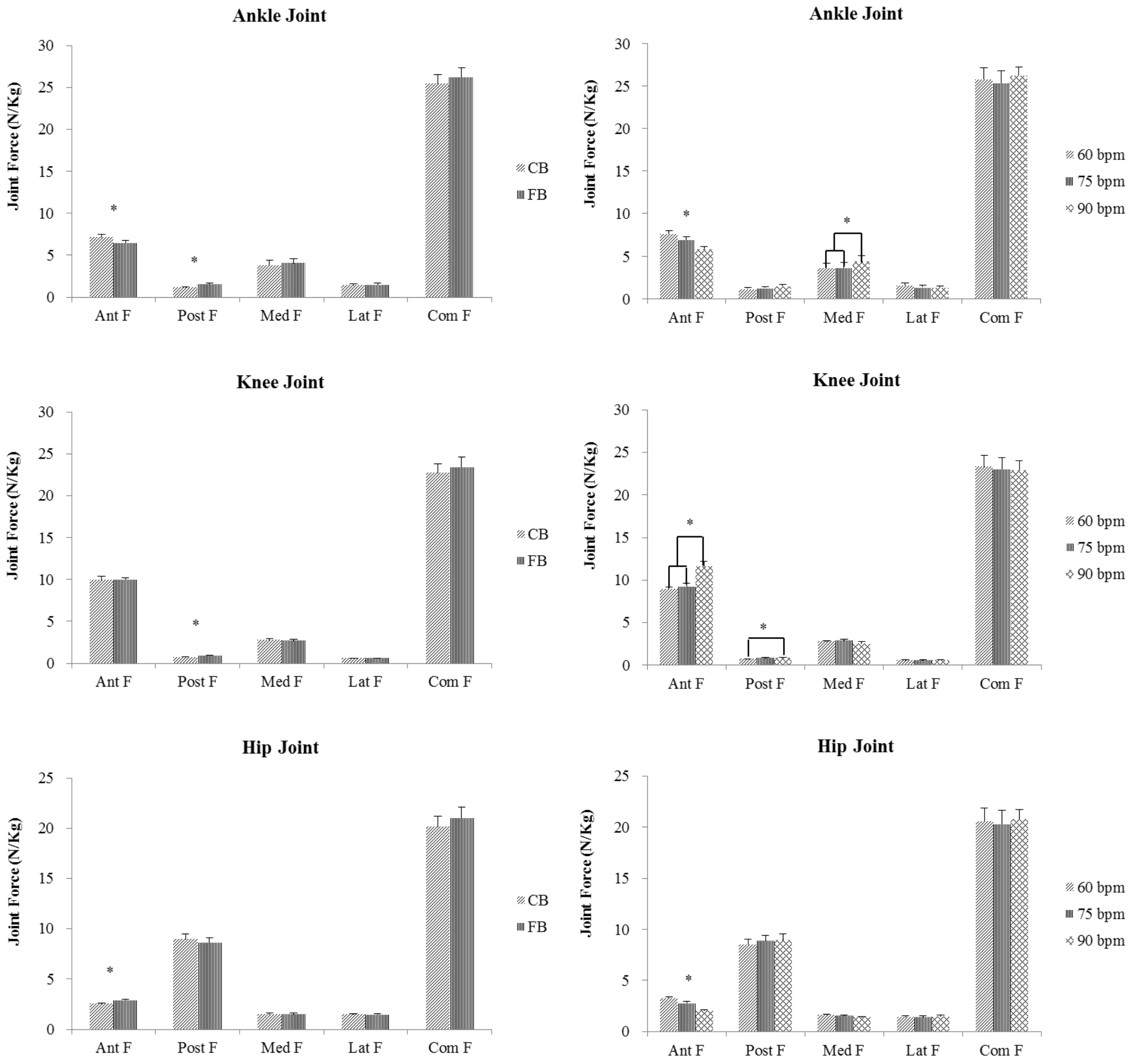

Figure 4.3. Peak joint forces of lower limbs in different box jumps and rates.

Note. *$p < .05$. CB: cross the box, FB: front the box.

Ant F: anterior shear force, Post F: posterior shear force, Med F: medial shear force, Lat F: lateral shear force, Com F: compression force.

4.4 Peak Joint Moments in Different Box Jumps

There was no interaction effect between different box jumps and rates for peak joint moments in lower limbs (Figure 4.4). For different box jumps, there was only one significant difference found in ankle dorsiflexor moment and which was greater in FB than in CB (Figure 4.4). As for different rates, in the circumstance of 90 bpm, joint moment appeared to be the greatest for knee extensor moment, ankle plantar flexor moment, and ankle internal rotation moment, while the opposite result was found in hip flexor moment (Figure 4.4).

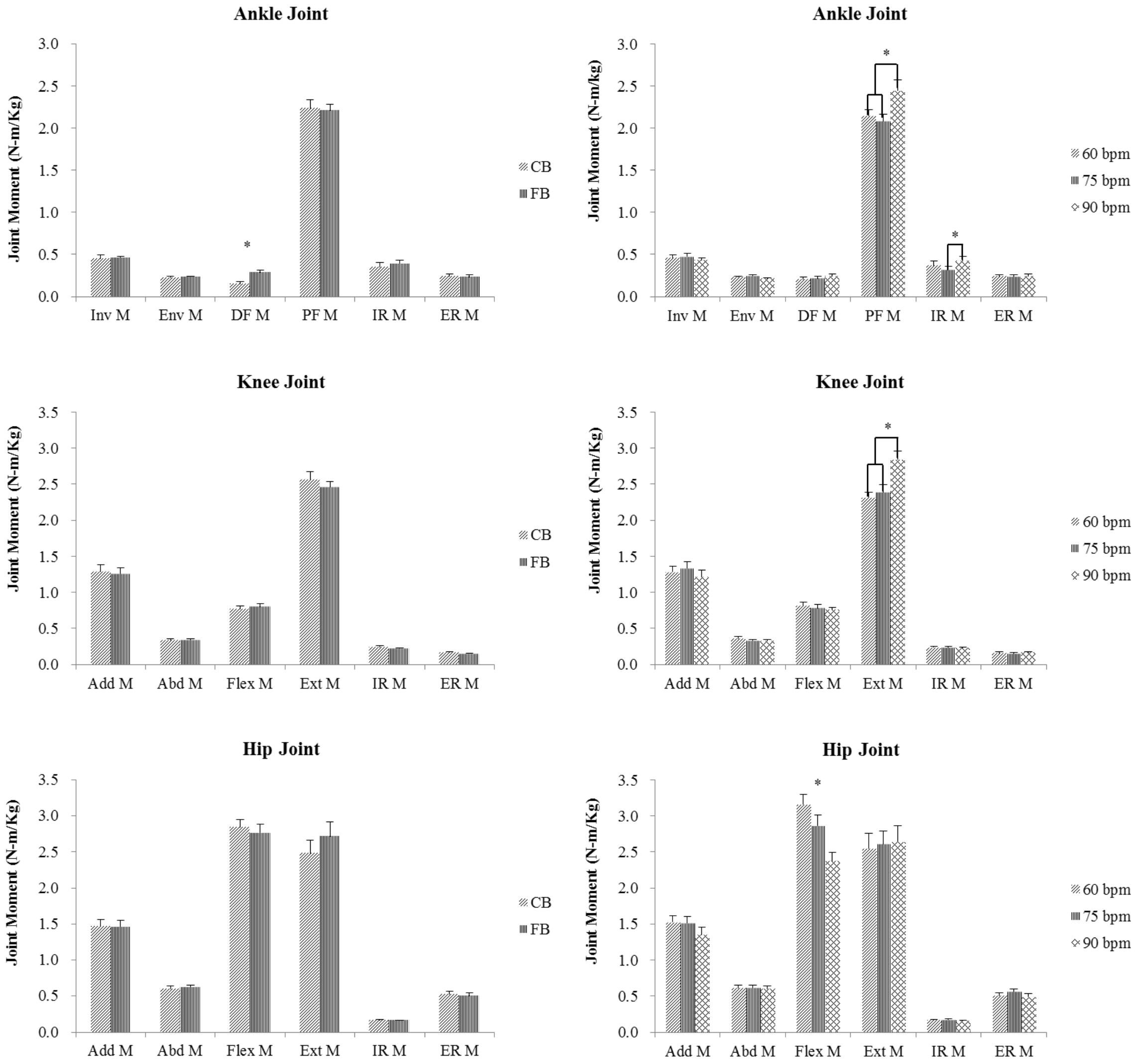

Figure 4.4. Peak joint moments of lower limbs in different box jumps and rates.

Note. *$p < .05$. CB: cross the box, FB: front the box.
Add M: adduction moment, Abd M: abduction moment, Flex M: flexor moment, Ext M: extensor moment, IR M: Internal rotation moment, ER M: external rotation moment. Inv M: inversion moment, Env M: eversion moment, DF M: dorsiflexor moment, PF M: plantar flexor moment.

Chapter 5 Discussion

5.1 Joint Kinematics & Kinetics during Different Box Jumps

CB and FB were two similar jumps with the same setting of the boxes. Because of their properties of movement, we assumed that when subjects performed CB, they have to put more effort on horizontal displacement and joint flexion of lower extremities are needed for the purpose of crossing the box compared with FB. As for FB, there seemed to be more vertical component during the jump that may address less on joint flexion of lower extremities.

Changing the speed of the task was thought to be a means to adjust the intensity in plyometric exercises (Houglum, 2001). In the empirical training regimens, athletes are always told that - the faster, the better. Therefore, in the present study, we set the rates as 60 bpm, 75 bpm, 90 bpm to investigate how the low-to-high rates affect the biomechanical parameters of the jumps. It is not hard to speculate that the higher the rate, the higher the intensity; thus, we assumed that the biomechanical parameters involved in any changes with the rates should be in a linear relationship as well.

The literatures about different box jumps and rates were limited. Most studies such as the evaluations of the intervention effects as well as the intensity of plyometric exercises investigated maximal heights, peak ground reaction forces, joint angles, foot contact times of maximal exertion of the vertical jumps. The difference between the present study and the previous ones was that we didn’t emphasize on the maximal effort of the performance but we investigated the patterns instead.

As for joint angles, generally speaking, subjects needed to flex hip joint and knee joint more at a certain checkpoint in order to cross over the box safely in CB than in FB. The joint angles of the ankle may indicate that subjects landed with lateral border of midfoot at landing; then they transformed the foot pressure from lateral border to medial border before the checkpoint of peak landing force. This may be able to be compared to the transition of foot pressure during the gait cycle, and yet the dissimilarity was that subjects landed with midfoot in this study, while the landing portion was heel in gait cycle.

Lephart et al. (2005) noted that increased hip flexion at initial contact, and increased peak knee flexion as well as time to peak knee flexion in jump-landing task provided the desired effect for body to absorb the joint forces more effectively. Furthermore, hamstrings were thought to be tensioned more by increasing angles of hip and knee flexion, thus a posterior force would be created additionally to prevent ACL from overstressed. We may not be able to directly compare our result to Lephart's conclusion, since his study was about the comparison of pre- and post- intervention of plyometric exercise and resistance training. However, it gave us the notion that if subjects performed more hip and knee flexion at the checkpoints he mentioned in his study during a jump-landing task, the risk of ACL injury may be lessened. According to the patterns of kinematics in the present study, less hip and knee flexion were found in FB at the checkpoint of landing, but more knee flexion was also found in FB at the checkpoint of maximum knee flexion; however, more hip and knee flexion were found in CB at the checkpoint of landing, but less knee flexion was also found in CB at the checkpoint of maximum knee flexion. This result may indicate that while performing CB, subjects might have better force absorptions at the checkpoint of landing; however, while performing FB, subjects may have a better stabilization for ACL at the checkpoint of maximum knee flexion. As for time to maximum knee flexion, there were no statistical differences between different jumps under each rate.

As for joint moments, it was found in both CB and FB that the peak hip flexor moment took place after the checkpoint of landing and before the checkpoint of peak landing force, while peak hip extensor moment was noted several milliseconds after the checkpoint of peak landing force. It indicated that both jumps required hip flexor and hip extensor to activate reciprocally from the checkpoint of landing to the checkpoint of maximum knee flexion in order to absorb the impact forces and then hip extensor carried out through the checkpoint of maximum knee flexion to take-off for the preparation of next jump. Hip abduction moment could be noted in both jumps before the checkpoint of landing; this was consistent with Lephart's finding (2005). According to his study, he suggested that the activation of gluteus medius prior to the initial contact could allow subjects to position their thighs in order to cope with undesired hip adduction and knee valgus caused by impact force at landing; in this way, knee stability would be increased. Hip adduction moment and hip external rotation moment were found in FB throughout from landing to take-off; however, in CB, it was first hip adduction moment and hip external rotation moment took place before the checkpoint of maximum knee flexion, then hip abduction moment took over after. Either way, both hip adductor and hip abductor were more likely to function as assisters for keeping knee joints to a more neutral frontal plane position (Chimera, 2004). The moment of hip external rotation was more obvious in FB than in CB. Because hip external rotator acts as the stabilizer in hip joint by driving femoral head into acetabulum during stance phase of gait cycle, we probably could refer it to the current study that subjects may require more activation of hip external rotator to stiffen hip joint and to keep hip joint in slight external rotation while performing FB.

In the knee joint, knee extensor activated throughout the jump both in CB and FB. This indicated that before the checkpoint of maximum knee flexion, knee extensor was passively stretched and acted as a decelerator, while after that point it acted as an accelerator for the next jump. There was one interesting finding needed to be mentioned that a peak of knee flexor moment was only found in FB around the checkpoint of peak landing force. In a knee injury review (Dugan, 2005), the role of hamstrings was suggested to be important in the co-contraction of hamstrings and quadriceps at landing task because hamstrings were thought to be the synergistic stabilizer of ACL. Back to this peak knee flexor moment found in the current study, it was possible that while performing FB, the activation of hamstrings would be recruited more around the checkpoint of peak landing force. Knee adduction moment was also noted in both jumps and at the time it activated was consistent with when knee extensor moment occurred. One recent research suggested that adduction/abduction moment at knee joint was able to be actively produced by hamstrings and quadriceps co-contraction and was used to resist the externally applied adduction/abduction moment. In this case, the activation of knee adductor in the present study may act as a resistance against knee valgus while landing to prevent injury.

In the ankle joint, ankle plantar flexor activated throughout from the checkpoint of landing to take-off. In both CB and FB, plantar flexor served as the decelerator before the checkpoint of maximum knee flexion, and then became the accelerator after that. A slight increase in ankle dorsiflexion may provide an extra stretch to generate the following forceful contraction of plantar flexor at the checkpoint of take-off. There were two obvious peak moments of plantar flexor found in FB after the checkpoint of landing and before the checkpoint of take-off; however there was only one notable peak moment of plantar flexor found in CB before the checkpoint of take-off. This may indicate that FB required more plantar flexor activation for the deceleration around the checkpoint of peak landing force. As for ankle inversion/eversion moment, FB had a more dominant inversion moment than CB throughout from the checkpoint of landing to take-off. Ankle inversion moment in CB was similar to which in FB before the checkpoint of maximum knee flexion, whereas ankle eversion moment was found after that. As for the moment of ankle internal/external rotation, ankle external rotation moment was found carried out from the checkpoint of landing to take-off in CB, but which was found to be ankle internal rotation moment in FB during the same period of time. The result may indicate that subjects landed with more supinated foot before the checkpoint of maximum knee flexion in FB than in CB. After the checkpoint of maximum knee flexion and until the checkpoint of take-off, a more eversion joint angle combined with a more inversion moment could be found in FB, while a slight inversion joint angle accompanied with a slight eversion moment was found in CB. It was possible that either the eversion moment in CB or inversion moment in FB was working as the counter-part with joint angles resulted from landing force in order to provide a better ankle position for the contraction of plantar flexor.

According to the pattern of joint forces, there were two notable compression forces after the checkpoint of landing as well as the checkpoint of peak landing force respectively for each joint during both box jumps. First peak could be caused by the impact force and the second peak could be caused by the peak landing force. The value of peak joint compression force was decreased in the order of ankle, knee and hip; however, all of them were around 30 times body weight.

In the hip joint and for both jumps, there were posterior shear forces found after the checkpoint of peak landing force until the checkpoint of take-off and with medial shear forces accompanied during the jumps. Both of them reached to their peaks when peak hip compression force happened. Therefore, after 0.008 seconds of the checkpoint of peak landing force, hip joint would receive a compression force with the shear force in posterior-medial direction.

In the knee joint, anterior shear force took place throughout the jump which was also accompanied with medial shear force. Both of their peaks were found at the point when knee joint was suffering from the peak compression force after 0.008 seconds of the checkpoint of peak landing force. This may indicate that there was a predisposition of ACL as well as bilateral collateral ligaments (MCL and LCL) to be stressed during the box jumps especially at the point right after the checkpoint of peak landing force.

In the ankle joint, peak compression force also happened at the same point as hip and knee joint. Anterior shear force occurred during the jump for both CB and FB, and peak lateral shear force could be found when peak anterior shear force took place. The minor difference of joint forces between CB and FB was that there was a tendency in FB for lateral shear force transformed into medial shear force after the checkpoint of maximum knee flexion.

To sum it up, subjects in the current study were all well-trained competitive athletes specialized in long jump and high jump. Their performances were rather standardized and consistent in each trial according to the analysis results in this experiment. Therefore, the patterns of kinematics and kinetics may be able to be regarded as the contrast to subjects from different populations or conditions in the further studies.

5.2 Range of Motion (ROM)

There were interaction effects between box jumps and rates in ROM of hip flexion/extension and ankle internal/external rotation. In different box jumps under different rates, the ROM of hip flexion/extension was found significantly greater in CB than in FB among all rates (60 bpm, 75 bpm and 90 bpm). This could be caused by the less hip flexion in FB at the checkpoint of landing, take-off and especially the last maximum jumping height at which subjects had to flex hip joint more to cope with the height of the last box. As for ankle internal/external rotation, only when it reached to 90 bpm a significantly lesser ROM could be found in CB than in FB. This may due to the movement pattern in FB of ankle internal/external rotator which activated more before and after the checkpoint of maximum knee flexion; therefore, it was possible that higher rate required more controls of this movement.

While in different rates under different box jumps, significant differences were only appeared in FB instead of CB. ROM of hip flexion/extension was found significantly greater in both 60 bpm and 75 bpm than in 90 bpm, while 60 bpm and 75 bpm had no significant difference. It seemed that hip flexion/extension and ankle internal/external rotation in CB were not affected by different rates. However, the ROM of hip flexion/extension and ankle internal/external rotation in FB were influenced more by different rates. It was possible that subjects performed less ROM of hip flexion/extension in 90 bpm in order to keep up with the pace. There was a tendency that the ROM of hip flexion/extension decreased in an order of 60 bpm, 75 bpm and 90 bpm, but there was no significant difference found between 60 bpm and 75 bpm. There was an interesting finding for the ROM of ankle internal/external rotation that which was significantly lesser in 75 bpm than in both 60 bpm and 90 bpm. However, the reason seemed to be still unresolved.

There were several findings in non-interaction effects. In a knee injury review (Dugan, 2005), adduction and internal rotation of the femur was emphasized to be avoided during landing because those would result in increasing the risk of ACL injury. Although the ROM of hip internal/external rotation was found statistically greater in FB than in CB and also the greatest in 75 bpm among all the velocities, there was still lacking of evidence to conclude that the undesired hip internal rotation did actually happen in both conditions. According to the patterns of kinematics in hip joint, hip external rotation was found remaining throughout the jumps in both CB and FB. However, the decreased joint angle of hip external rotation could be noticed in FB at the checkpoint of maximum knee flexion and it would last until the mid-point of the time between the checkpoints of maximum knee flexion and take-off. Therefore, the greater ROM deviation of hip internal/external rotation found in FB and 75 bpm in the current study could probably only indicate that the tendency of ACL being stressed in both conditions would become the true risk when slight hip external rotation transformed into hip internal rotation during the landing task.

For the knee joint, significant differences of ROM were found in knee flexion/extension and adduction/abduction for different box jumps. CB compared with FB had more ROM of knee flexion/extension and adduction/abduction during the landing task. Excessive knee adduction/abduction should be avoided because of the reason that improper position of the knee joint such as knee valgus during the landing task is the predisposition of ACL injury (Dugan, 2005; Lephart et al., 2005). Therefore, based on our result, FB seemed to have less undesired motion of knee adduction/abduction which was probably the safer landing position of the knee joint. It was not hard to understand the reason why ROM of knee flexion/extension was significant greater in CB than in FB due to their kinematic patterns.

According to the statistical findings of present study, the ROM of knee joint seemed to be influenced by different rates more than the ROM of hip and ankle joints in all directions including flexion/extension, adduction/abduction and internal/external rotation. No matter in which direction, the least ROM of knee joint was found at 90 bpm. This may indicate that up to 90 bpm, subjects would perform a stiffer landing pattern with less frontal plane deviation of knee joint as well as less tibia rotation; both of those may relate to a better athletic performance by utilizing stretch-shortening cycle better (Horita et al., 2002) and also a safer landing position by reducing the risk factor of ACL injury (Dugan, 2005).

To sum it up, excessive dynamic valgus including increased hip adduction, knee valgus and ankle eversion was suggested to be avoided to reduce the incidence of non-contact ACL injury. In the present study, FB and 90 bpm were found to have less predisposing factors mentioned above.

5.3 Joint Forces and Joint moments

In the previous studies, Ground reaction forces at difference phases were mostly utilized to describe the impacts on the joints to evaluate the predisposition of injuries or the effect of the training protocols (Heweet, 1996; Irmischer, 2004). In this study, we investigated the joint forces in the lower extremities while performing different box jumps with different rates to understand the stress that may impose to soft tissues surrounding the joints.

Joint forces, or intersegmental forces, could be created internally or externally. Internal factors include muscles, bone-to-bone and ligaments, while external factors include external force, gravity and inertia. In the present study, we discussed the influence of the impact force caused by the ground reaction force upon the joints of lower extremities.

For different box jumps, there were several joint forces found greater while performing FB than CB; they were anterior shear force in the hip joint, posterior shear force in the knee joint and posterior shear force in the ankle joint. Among all these joint forces mentioned above, posterior shear force in the knee joint would be considered the most because of the prevalence of knee injuries in the sport fields. The greater posterior shear force in the knee joint found in FB may indicate that posterior cruciate ligament (PCL) would be stressed more in FB than in CB. Although PCL injury was less discussed in the sport field compared with ACL injury, the result still gave us the notion that for those who have PCL injuries, FB should probably be implemented in the later stage and after the strength of quadriceps has built up. According to the findings of the current study, the most concerned issue of anterior shear force which could lead to non-contact ACL injuries was found non-significant between CB and FB.

When it comes to different rates, knee anterior shear force, knee posterior shear force and ankle medial shear force were found statistically greatest at the rate of 90 bpm than at 60 pbm or 75 bpm. This may indicate that jumping with a higher rate would impose more stress on knee ACL as well as posterior cruciate ligament (PCL) and also three ligaments on the lateral side of the ankle joint (anterior & posterior talofibular ligament and calcaneofibular ligament) which may possess higher risk of inversion sprain. Although there were no statistically differences found between 60 pbm and 75 bpm, the value of those joint forces mentioned above, from low to high, were ranked in an order of 60 pbm, 75 bpm, and 90 bpm. Since the intensity could also be defined as the stress of the task, this was correspondent with the notion that the intensity of plyometric exercises could be increased by the higher speed. (Houglum, 2001; Chu, 1998).

As for joint moments in different box jumps, the only significant difference between CB and FB was ankle dorsiflexor moment. However, when we compared the flexor moments and extensor moments of hip, knee and ankle joint, we found that, though the difference between CB and FB were not statistically significant, CB had greater values in hip flexor moment, knee extensor moment and ankle plantar flexor moment than FB, while FB had greater values in hip extensor moment, knee flexor moment and ankle dorsiflexor moment. This was consistent with the kinetic patterns of FB that there was a peak knee flexor moment found only in FB instead of CB before the checkpoint of peak landing force. The tendency above may indicate that subjects needed to utilize different neuromuscular strategies to perform CB and FB respectively. On the other hand, we may be able to say that different box jumps evoke activations of different muscle groups; therefore, we may be able to apply them to train the certain muscle groups we desire to emphasize.

When it comes to different rates, knee extensor moment, ankle plantar flexor moment, and ankle internal rotation moment were found the greatest at the rate of 90 bpm. In contrast, the value of hip flexor moment was found the least at the rate of 90 bpm. Again, we compared the significant and non-significant results of the flexor moments and extensor moments of hip, knee and ankle joint among all rates, we found that 90 bpm was greater than 60 bpm and 75 bpm in hip extensor moment, knee extensor moment, ankle plantar flexor moment as well as dorsiflexor moment, however, at the same time, there seemed to be no significant difference between 60 and 75 bpm in most occasions. As for hip flexor moment and knee flexor moment, the values were found the greatest at the rate of 60 bpm. According to the findings of the current study, up to 90 bpm was probably the most pertinent rate to utilize stretch-shortening cycle (SSC) to train the extensors of the lower limbs, while 60 bpm could be implemented to prevent muscle imbalance by training the flexors of the lower extremities.

The lack of statistically significant differences of joint moments in different box jumps as well as in different rates could result from the insufficient numbers of the subjects. However, the trend of the joint moments found in the current study gave us the notions that different box jumps and different rates could be applied to the training regimen for selective muscle activations. This is important because different sports have different demands of neuromuscular strategies and also the ultimate goal is to enhance the performance in the competitions or to be ready to return to play. In the point of view of ACL injury prevention program, knee anterior shear force should be minimized as well as knee valgus/varus moment and internal/external rotation moment in order to keep knee joint in a better neutral position during the task. In the current study, FB had lower values of those contributing factors than CB. Although at the rate of 90 bpm, knee anterior shear force was the greatest among all, it had the lowest value among all in other factors.

Chapter 6 Conclusion

Overall speaking, as for the ACL injury prevention program or for the post-injured athletes, FB is probably the better box jump to be included in the training protocols due to its less undesired dynamic valgus found in ROM, joint forces and joint moments.

The jumping speeds set in the current study were considered to be the submaximal intensity according to Chu’s notions (1998); therefore, they are more suitable for the beginning sessions or the athletes in the return-to-sports phase of rehabilitation. As a general rule, training at the rate of 90 bpm is recommended because of the benefit from the effect of stretch-shortening cycle (SSC) and because of the better landing position as well as less undesired moments.

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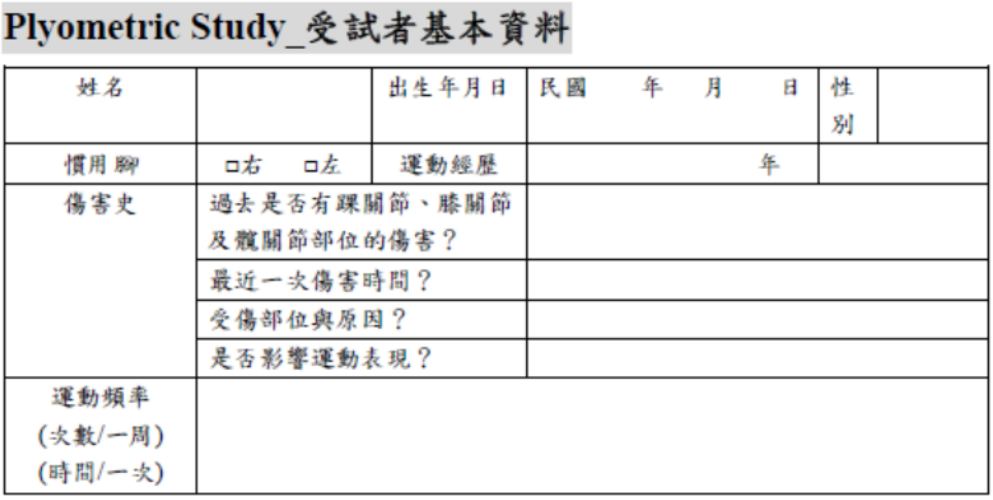
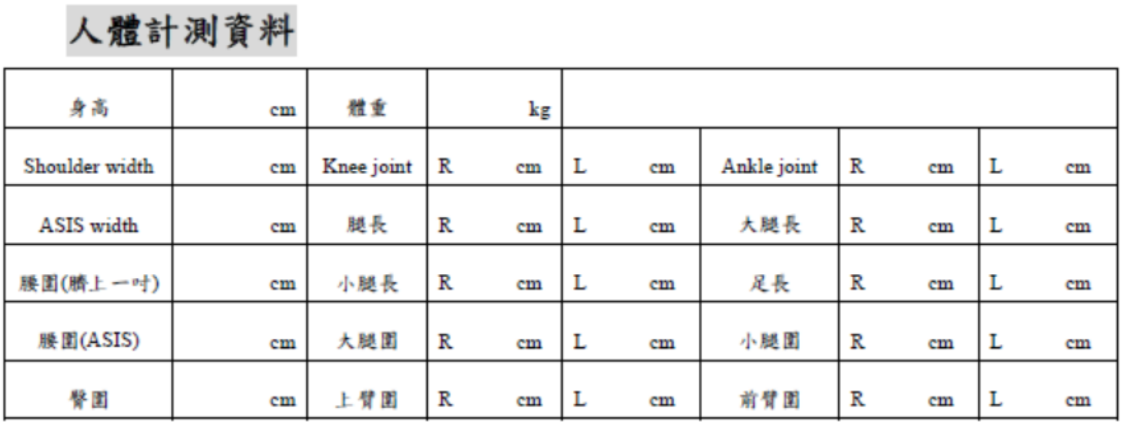
Appendix A



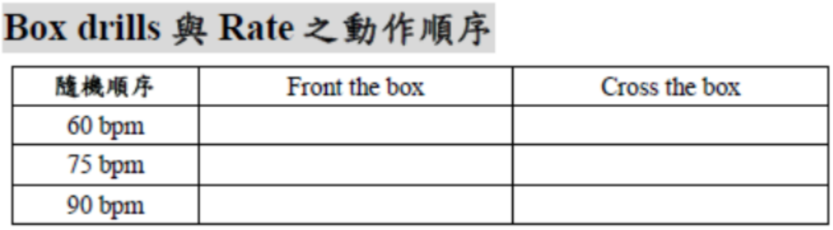
Plyometric Study_受試者基本資料

姓名		出生年月日	民國　　年　　月　　日	性別	
慣用腳	□右　　□左	運動經歷	年		
傷害史	過去是否有踝關節、膝關節及髖關節部位的傷害？				
	最近一次傷害時間？				
	受傷部位與原因？				
	是否影響運動表現？				
運動頻率 (次數/一周) (時間/一次)					



人體計測資料

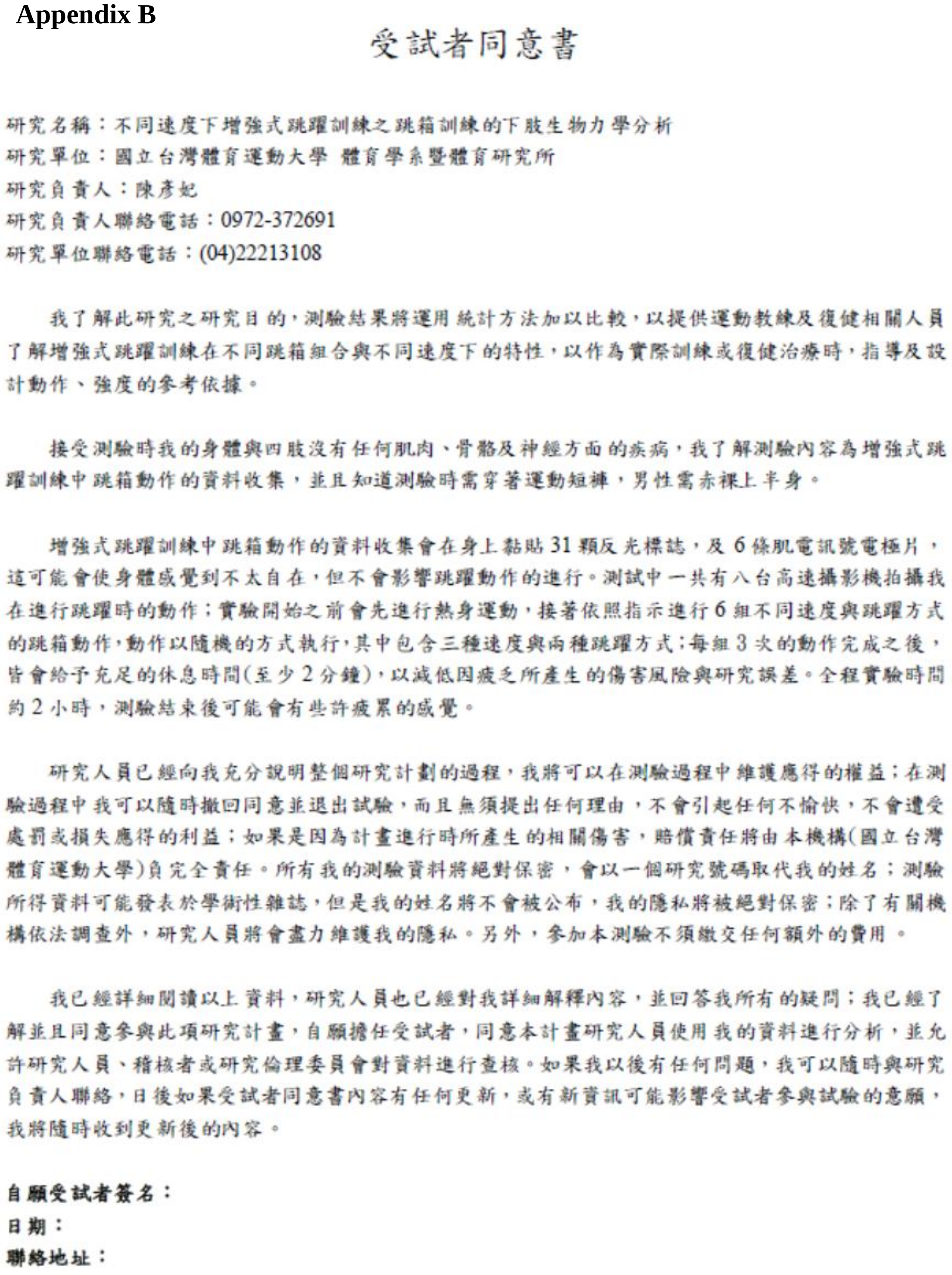
身高	cm	體重	kg					
Shoulder width	cm	Knee joint	R　　cm	L　　cm	Ankle joint	R　　cm	L　　cm	
ASIS width	cm	腿長	R　　cm	L　　cm	大腿長	R　　cm	L　　cm	
腰圍(臍上一吋)	cm	小腿長	R　　cm	L　　cm	足長	R　　cm	L　　cm	
腰圍(ASIS)	cm	大腿圍	R　　cm	L　　cm	小腿圍	R　　cm	L　　cm	
臀圍	cm	上臂圍	R　　cm	L　　cm	前臂圍	R　　cm	L　　cm	



Box drills 與 Rate 之動作順序

隨機順序	Front the box	Cross the box
60 bpm		
75 bpm		
90 bpm		

Appendix B



受試者同意書

研究名稱：不同速度下增強式跳躍訓練之跳箱訓練的下肢生物力學分析
研究單位：國立台灣體育運動大學 體育學系暨體育研究所
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我了解此研究之研究目的，測驗結果將運用統計方法加以比較，以提供運動教練及復健相關人員了解增強式跳躍訓練在不同跳箱組合與不同速度下的特性，以作為實際訓練或復健治療時，指導及設計動作、強度的參考依據。

接受測驗時我的身體與四肢沒有任何肌肉、骨骼及神經方面的疾病，我了解測驗內容為增強式跳躍訓練中跳箱動作的資料收集，並且知道測驗時需穿著運動短褲，男性需赤裸上半身。

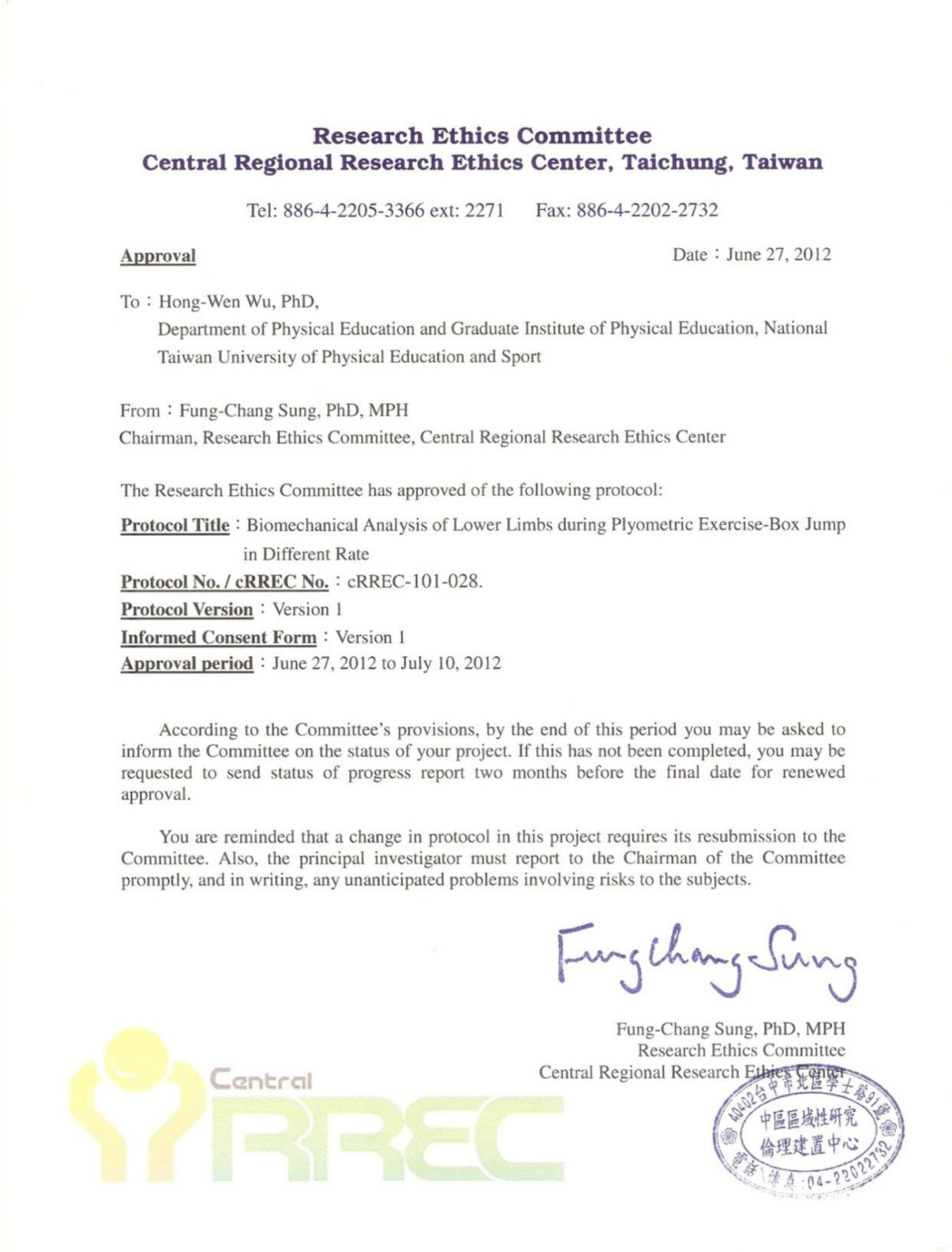
增強式跳躍訓練中跳箱動作的資料收集會在身上黏貼31顆反光標誌，及6條肌電訊號電極片，這可能會使身體感覺到不太自在，但不會影響跳躍動作的進行。測試中一共有八台高速攝影機拍攝我在進行跳躍時的動作；實驗開始之前會先進行熱身運動，接著依照指示進行6組不同速度與跳躍方式的跳箱動作，動作以隨機的方式執行，其中包含三種速度與兩種跳躍方式；每組3次的動作完成之後，皆會給予充足的休息時間(至少2分鐘)，以減低因疲乏所產生的傷害風險與研究誤差。全程實驗時間約2小時，測驗結束後可能會有些許疲累的感覺。

研究人員已經向我充分說明整個研究計劃的過程，我將可以在測驗過程中維護應得的權益；在測驗過程中我可以隨時撤回同意並退出試驗，而且無須提出任何理由，不會引起任何不愉快，不會遭受處罰或損失應得的利益；如果是因為計畫進行時所產生的相關傷害，賠償責任將由本機構(國立台灣體育運動大學)負完全責任。所有我的測驗資料將絕對保密，會以一個研究號碼取代我的姓名；測驗所得資料可能發表於學術性雜誌，但是我的姓名將不會被公布，我的隱私將被絕對保密；除了有關機構依法調查外，研究人員將會盡力維護我的隱私。另外，參加本測驗不須繳交任何額外的費用。

我已經詳細閱讀以上資料，研究人員也已經對我詳細解釋內容，並回答我所有的疑問；我已經了解並且同意參與此項研究計畫，自願擔任受試者，同意本計畫研究人員使用我的資料進行分析，並允許研究人員、稽核者或研究倫理委員會對資料進行查核。如果我以後有任何問題，我可以隨時與研究負責人聯絡，日後如果受試者同意書內容有任何更新，或有新資訊可能影響受試者參與試驗的意願，我將隨時收到更新後的內容。

自願受試者簽名：
日期：
聯絡地址：

Appendix C



Research Ethics Committee
Central Regional Research Ethics Center, Taichung, Taiwan

Tel: 886-4-2205-3366 ext: 2271 Fax: 886-4-2202-2732

Approval Date：June 27, 2012

To：Hong-Wen Wu, PhD,
Department of Physical Education and Graduate Institute of Physical Education, National Taiwan University of Physical Education and Sport

From：Fung-Chang Sung, PhD, MPH
Chairman, Research Ethics Committee, Central Regional Research Ethics Center

The Research Ethics Committee has approved of the following protocol:

Protocol Title：Biomechanical Analysis of Lower Limbs during Plyometric Exercise-Box Jump in Different Rate

Protocol No. / cRREC No.：cRREC-101-028.

Protocol Version：Version 1

Informed Consent Form：Version 1

Approval period：June 27, 2012 to July 10, 2012

According to the Committee's provisions, by the end of this period you may be asked to inform the Committee on the status of your project. If this has not been completed, you may be requested to send status of progress report two months before the final date for renewed approval.

You are reminded that a change in protocol in this project requires its resubmission to the Committee. Also, the principal investigator must report to the Chairman of the Committee promptly, and in writing, any unanticipated problems involving risks to the subjects.

Fung-Chang Sung

Fung-Chang Sung, PhD, MPH
Research Ethics Committee
Central Regional Research Ethics Center

中區區域性研究
倫理建置中心